Attachment N

Exponent Report on PG&E Caribou-Palermo Asset Condition Investigation

November 1, 2019

PG&E Caribou-Palermo Asset Condition Investigation

November 1, 2019

CAMP-0543

Exponent®

PG&E Caribou-Palermo Asset Condition Investigation

Prepared for

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Executive Summary

Following the November 2018 Camp Fire, Pacific Gas and Electric (PG&E) conducted enhanced inspections of its electric transmission lines within higher wildfire risk areas. The bulk of these enhanced inspections were conducted as part of PG&E's Wildfire Safety Inspection Program (WSIP). These inspections indicated that the Caribou-Palermo line, reportedly associated with the Camp Fire, exhibited a relatively high number of high-priority corrective work orders, denoted "tags", compared to other PG&E transmission lines examined. Exponent was retained by PG&E and the California Public Utilities Commission (CPUC) to conduct an independent analysis of the cause of the reportedly high numbers of high-priority tags on Caribou-Palermo compared with other, similar lines.

Exponent examined comparison lines, selected based on voltage, tower design, location, elevation, presence of guest circuits, and age criteria. To help compare the number of high-priority corrective action issues between Caribou-Palermo and the comparison lines, Exponent reviewed the following: condition assessments and corrective action work orders from PG&E's post–Camp Fire inspections, asset information (GIS data), historical construction records, historical wind and weather data, maintenance/inspection records, historical corrective action work orders, outage data, and available drone inspection images for select lines. Exponent also conducted multiple interviews with PG&E subject matter experts (SMEs).

Based on our analysis, we have reached the following conclusions:

1. The Caribou-Palermo line was confirmed to have greater post–Camp Fire high-priority ("A" + "B") repair tag counts than all selected comparison lines, as well as an increased per-structure high-priority tag rate when normalized for the number of steel lattice towers.

2. Other lines adjacent to Caribou-Palermo such as Bucks Creek–Rock Creek–Cresta (BCRC), Cresta–Rio Oso (CRO), and Paradise–Table Mountain (PTM) had the second, fourth, and fifth highest post–Camp Fire high-priority tag counts, respectively, when normalized for steel lattice towers. Pit #4 Tap (P4T) had the third highest normalized high-priority tag count, but is not near Caribou-Palermo.

3. Cold-end insulator hardware-related issues were responsible for the highest number of "A" priority post–Camp Fire tags on Caribou-Palermo, and the second highest number of "B" priority tags. Foundation-related issues accounted for the greatest number of "B" tags.

4. Wear was the most commonly observed post–Camp Fire damage mechanism for Caribou-Palermo "A" tags and second most commonly observed damage mechanism for "B" tags. Nearly all Caribou-Palermo wear-related tags were associated with cold-end hardware. Cold-end hardware wear issues were likely caused by repeated conductor and insulator movement over time.

5. Caribou-Palermo, BCRC, and CRO lines, each located within the North Fork Feather River Canyon, exhibited high-priority cold-end hardware wear tag counts more than three times higher than the next highest comparison line when normalized for steel lattice towers.

6. Link connections were observed only on the southern portion of Caribou-Palermo and accounted for approximately 40-percent of cold-end hardware wear tags on the entire line. All of the Caribou-Palermo South wear tags were associated with link connections.

7. Roughly one-sixth of drone-imaged Caribou-Palermo North towers contained insulated jumpers. However, over 60-percent of the post–Camp Fire high-priority cold-end hardware wear tags on Caribou-Palermo North were associated with structures that contained insulated jumpers. Additionally, over half of all cold-end hardware wear tags on BCRC and CRO were on towers with insulated jumpers.

8. Caribou-Palermo North and other North Fork Feather River Canyon comparison lines contained an increased number of insulated jumpers (and insulated jumper wear tags) compared to similar lines. These Caribou-Palermo and other North Fork Feather River Canyon structures with insulated jumpers exhibited a higher incidence of cold-end hardware wear than standard suspension structures.

9. Caribou-Palermo North experiences higher annual average wind speeds than non-adjacent comparison lines. Lines analyzed within the North Fork Feather River Canyon may have increased wear tag rates associated with longer-duration high-wind conditions. No apparent correlation between wear tags and temperature, precipitation, or peak wind speed (50-year return) was observed.

10. From 2001 to November 2018, the Caribou-Palermo line was subjected to similar ground inspection and patrol frequencies as comparison lines. These inspections and patrols yielded comparable normalized high-priority tag counts between Caribou-Palermo and comparison lines.

11. Historical ground and patrol inspection forms did not specify cold-end hardware assessment. Pre-Camp Fire climbing inspection forms did contain assessment fields for structural components such as insulator hardware. However, climbing inspections were not routinely performed on lines less than 500kV.

12. Although climbing inspections were not routinely performed on lines less than 500 kV, 79 Caribou-Palermo towers were subjected to climbing inspections in the months prior to the Camp Fire. The tower reportedly associated with the Camp Fire was not inspected. PG&E's post–Camp Fire enhanced inspection procedures, including CIRT or DIRT reviews, have led to substantial improvements in identifying progressive or wear-related insulator hardware damage.

13. The Caribou-Palermo line had more normalized equipment-based outages between 2007 and 2018 than approximately 80 percent of the other WSIP transmission lines.

14. Caribou-Palermo and other North Fork Feather River Canyon lines appear to have a unique set of factors that contributed to increased rates of high-priority cold-end hardware tags relative to other comparison lines. Factors such as design (link connectors and a relatively large number of non-tensioned insulated conductors), long-duration exposure to higher winds, age, and historical inspection methodologies likely all contributed to these cold-end hardware wear issues.

Note that this Executive Summary does not contain all of Exponent's technical evaluations, analyses, conclusions, and recommendations. Hence, the main body of this report is at all times the controlling document.

Limitations

At the request of PG&E and the CPUC, Exponent, Inc. (Exponent) has reviewed information related to the Caribou-Palermo electric transmission line and selected comparison lines. Documents and information reviewed included condition assessments, corrective action work orders, GIS data, historical construction records, wind and weather data, maintenance/inspection records and procedures, outage data, and available drone inspection images. When possible, the timing associated with these data is provided in this report. Data outside the time ranges considered have not been evaluated. We have relied on PG&E to help select representative comparison lines and structures, as well as with regards to the quality and completeness of these data.

The scope of services performed during this investigation may not adequately address the needs of other users of this report, and any reuse of this report or its findings, conclusions, or recommendations presented herein is at the sole risk of the user. The opinions and comments formulated during this assessment are based on observations and information available at the time of the investigation. No guarantee or warranty as to future life or performance of any reviewed condition is expressed or implied.

The findings presented herein are made to a reasonable degree of engineering certainty. We have made every effort to accurately and completely investigate all areas of concern identified during our investigation. If new data become available or there are perceived omissions or misstatements in this report regarding any aspect of those conditions, we ask that they be brought to our attention as soon as possible so we may have the opportunity to fully address them.

Scope and Background

The purpose of our work was to investigate the reported high number of high-priority (“A” and “B”) corrective work orders found on the Caribou-Palermo line during enhanced inspections following the November 2018 Camp Fire. These enhanced inspections were primarily associated with PG&E’s Wildfire Safety Inspection Program (WSIP). Exponent has examined post–Camp Fire repair tag counts on Caribou-Palermo and selected comparison lines, and has assessed the frequency, locations, severity, components, and damage mechanisms associated with repair tags. Exponent has also compared historical weather conditions, maintenance and tag/corrective action history, and outage rates between Caribou-Palermo and comparison lines. Our analysis is based on information and documents provided by PG&E through September 2019. A list of documents and information provided to us is detailed below.

PG&E Enhanced Inspection and Repair Tag Process

Following the Camp Fire, PG&E conducted inspections to help assess the structural integrity of transmission line structures and components within wildfire-sensitive areas. As part of this enhanced inspection program, corrective work orders, “tags,” are generated to address specific corrective actions found in PG&E’s electrical transmission system. These tags are assigned a priority (A, B, E, or F) depending on the severity. These tags are then reviewed by PG&E’s Centralized Inspection Review Team (CIRT) or Drone Inspection Review Team (DIRT) to help calibrate and normalize corrective action priority. The priority assignments determine how quickly corrective action must be performed according to Table 1.

Table 1. Description of work tag priorities.

Tag Priority	Description
A	Perform corrective action immediately.
B	Perform corrective action within 3 months.
E	Perform corrective action within 12 months.
F	Perform corrective action in > 1 year.

Post–Camp Fire enhanced inspection transmission structures are typically visually inspected and documented during a climbing or aerial drone inspection. All electrical, structural, and general safety components are inspected to determine whether corrective action / repair is required. If an issue is observed, the inspector may create a preliminary “S5” work tag to address the problem. The “S5” designation indicates that this tag is in the “staging” process and requires further review by CIRT (or DIRT) before corrective action can begin. The results of these inspections, including photos of the structure and any inspector notes, are recorded digitally on “Pronto” forms, and are later reviewed by CIRT to make final corrective action priority decisions. CIRT review is prioritized based on incoming tag priority, i.e., priority “A” tags are reviewed first.

Once CIRT has approved an S5 notification, it gains the "LC" designation to indicate it is an official work tag and corrective action can begin.

During PG&E's enhanced inspection/ WSIP process, qualitatively higher rates of high-priority, "A" and "B" tags were reportedly noted on the Caribou-Palermo line, compared to other similar lines. Because of this, Exponent was asked to (1) evaluate whether the Caribou-Palermo line did in fact exhibit a greater number of high-priority tags compared to other, similar lines, and (2) help determine the cause of any increased high-priority tag rates. The methodology used to select comparison lines, assess tagged component frequencies, assess damage mechanisms, and examine environmental, design, maintenance/inspection history, and outage data are provided below.

Documents Reviewed

Exponent reviewed the following data, and relies on its accuracy for the purpose of this analysis:

- All post–Camp Fire high-priority corrective action work orders generated on Caribou-Palermo and comparison lines. This includes any S5 "staging" tags, closed LC tags where work was completed, and open LC tags that were not yet addressed at the time of the data pull, June 19, 2019.
    - All post–Camp Fire "E" and "F" priority tags on Caribou-Palermo were also analyzed.
- All pre–Camp Fire high-priority tags from February 1, 2000, to March 8, 2019, on Caribou-Palermo.
- Enhanced inspection Pronto forms, including both detailed climbing and nonclimbing inspections.
- Available drone inspection images as of May 3, 2019, for Caribou-Palermo and select lines, including Cresta–Rio Oso, Drum-Higgins, Drum–Rio Oso, Paradise–Table Mountain, and Bucks Creek–Rock Creek–Cresta.
- Asset information obtained from GIS data, including steel lattice tower designations, locations of towers, and conductor type and size.
- Detailed climbing inspection forms used in the inspections carried out prior to the Camp Fire in September through November 2018.
- Design books for towers on Caribou-Palermo and several comparison lines.
- Historical wind and weather data obtained from both PG&E records and public records.
    - NREL Wind Database: https://www.nrel.gov/grid/wind-toolkit.html
    - PG&E Document "Extreme Wind Speed Estimates Along PG&E Transmission Line Corridors"
- Historical maintenance and inspection records from 2001 to 2018.

- Equipment-based outages from 2007 to 2018.
- PG&E Electric Transmission Preventive Maintenance Manual (ETPM).
- Interview with PG&E subject matter experts regarding comparison line selection and general terminology.
- CalFire Camp Fire investigation photographs.
- Transmission Line Reference Book: *Wind Induced Conductor Motion*, EPRI, 1979

Methodology

Exponent conducted an analysis of the post–Camp Fire Caribou-Palermo corrective action / repair tags and compared them with other, similar lines. In particular, normalized (based on number of steel lattice structures) repair tag counts and damage mechanisms were compared. Potential contributing factors such as environment, age, maintenance/inspection practices, and design were investigated. Methodologies used for our analyses are described below.

Choice of Comparison Lines

Part of the scope of work was to compare the repair tag rates between Caribou-Palermo and other similar lines. These comparison lines were selected based on PG&E subject matter expert (SME) discussions and the following criteria:

- 115 or 230 kV lines only
- Elevations greater than 1,000 feet
- Single-circuit steel lattice towers
- Tier 2 or Tier 3 fire zones

Based on our discussions and the above criteria, a total of 43 comparison lines, including Caribou-Palermo (dual lines with #1 and #2 designations were grouped together), were selected. Of these 43 lines, 15 had fewer than 30 steel lattice towers and were not included in our analysis. Of the remaining 28 lines, nine lines are 115 kV (including Caribou-Palermo) and 19 are 230 kV. The complete list is given in Table 2 and mapped in Figure 1.

Of these 28 lines (including Caribou-Palermo), a subset of 6 lines were selected for further analysis: Caribou-Palermo (CP), Bucks Creek–Rock Creek–Cresta (BCRC), Cresta–Rio Oso (CRO), Drum–Rio Oso #1 and #2 (DRO), Drum-Higgins (DH), and Paradise–Table Mountain (PTM). These lines contain transposition towers with jumper arms installed prior to the 1950s, similar to the Caribou-Palermo incident tower reportedly involved in the Camp Fire. The subset of six lines underwent a systematic assessment, including tag analysis, component identification, geographic considerations for terrain and wind exposure, structure type/design, and cold-end hardware analysis. An additional line was added for detailed assessment: Pit#1-Cottonwood (P1C). P1C does not contain transposition towers with jumper arms; however, because it is a relatively long (>500 steel lattice towers) 230 kV line that contains significant portions in mountainous areas (>300 steel lattice towers over 1,000 feet), and was installed

around the same time as Caribou-Palermo, it was included in portions of the subset analysis. The remainder of this section outlines more specific details on the scope of the subset analysis and methodologies employed to identify the most prominent issues.

Table 2. Transmission lines considered and their steel lattice tower count. Lines selected for the analysis were given letter identifiers.

Voltage Rating	Comparison Lines	Identifier	SLT Count	SLT Count Over 1,000 ft	Approximate Install Date§
115 kV	Balch-Sanger	BS	175	85	1927
	Bell-Placer	-	22	-	-
	Bridgeville-Cottonwood	BC	195	192	1952
	Butte Valley-Caribou	BVC	49	49	1958
	Caribou-Palermo*	CP	423	294	1908
	Crag View-Cascade	-	12	-	-
	Drum-Higgins (DH)*	DH	152	152	1942
	Drum-Rio Oso #1 &2*	DRO	409	298	1913
	Drum-Summit #1 & 2	-	10	-	-
	Humboldt-Bridgeville	HB	37	34	-
	Humboldt-Trinity	-	8	-	-
	Kings River-Sanger-Reedley	-	15	-	-
	Paradise-Table Mtn*	PTM	63	39	1921
	Salt Springs-Tiger Creek	SSTC	128	128	1930
230 kV	Black Tap	-	3	-	-
	Bottle Rock Tap D.W.R.	-	6	-	-
	Bucks Creek-Rock Creek-Cresta*	BCRC	79	79	1928
	Carberry SW STA-Round Mtn	CRM	106	106	1924
	Caribou-Table Mtn	CTM	321	280	1958
	Cresta-Rio Oso*	CRO	179	164	1928
	Electra-Bellota	EB	197	65	1930
	Geysers #12-Fulton	G12F	94	52	1980
	Geysers #16 Tap	-	7	-	-
	Geysers #17-Fulton	-	7	-	-
	Geysers #18 Tap	-	3	-	-
	Haas-Mccall	HM	216	102	1958
	Helms-Gregg #1 &2	HG	433	299	1982
	Middle Fork-Gold Hill	MFGH	59	29	1966
	Pit #1-Cottonwood*	P1C	524	331	1924
	Pit #3-Carberry SW STA	P3C	85	85	1924
	Pit #3-Pit #1	P3P1	180	180	1924
	Pit #4 Tap	P4T	50	50	1954
	Pit #5-Round Mtn #1 & 2	P5RM	39	39	1943
	Pit #6 Jct-Round Mtn	-	13	-	-
	Pit #6 Tap	-	3	-	-
	Pit #7 Tap	-	8	-	-
	Poe-Rio Oso	PRO	352	72	1949
	Rock Creek-Poe	RCP	171	171	1949
	Round Mtn-Cottonwood #2 & 3	RMC	546	207	1924
	Santa Fe Geothermal Tap	-	7	-	-
	SPI (Burney) Tap	-	1	-	-
	Tiger Creek-Electra	TCE	101	99	1930
	Tiger Creek-Valley Springs	TCVS	131	131	1930

* Subset of lines included in the detailed analysis section.

§ Installation years listed typically do not apply to the entire present-day line and do not include structures that have been moved or replaced since their initial installation. The oldest date was chosen for lines that were installed at different times.

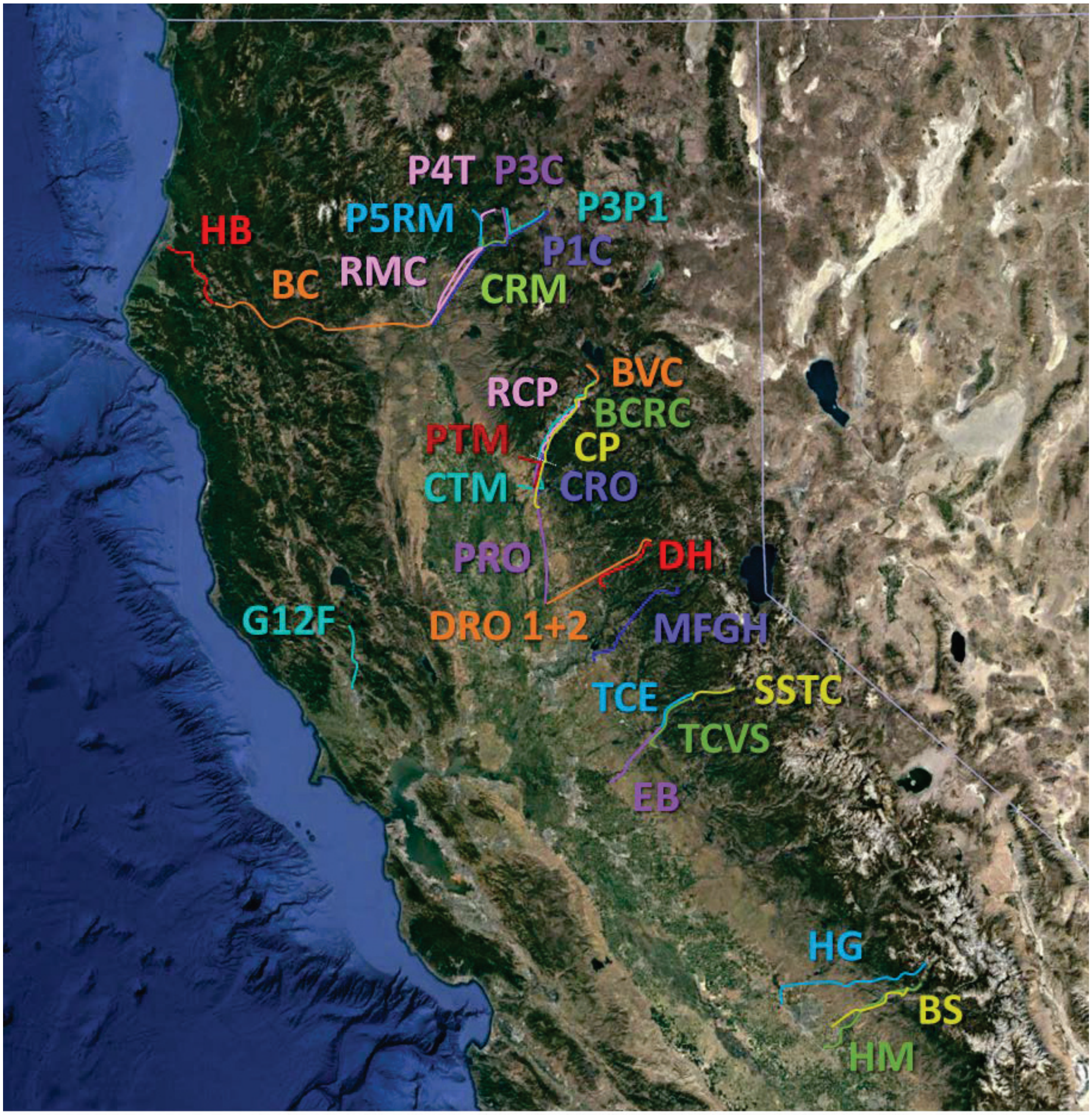


Figure 1. Line mapping overview of Caribou-Palermo and comparison lines utilized for the analysis detailed in this report.

Corrective Action Tag Review

All “LC” tags (issued after November 8, 2018, and prior to June 19, 2019) were compiled for the Caribou-Palermo and comparison lines. Using the inspector’s text regarding the inspected structure, the high-priority “A” and “B” tags were binned into categories based on the component responsible for the corrective tag and the damage mode. The number of tags associated with each component and damage mechanism was then identified, plotted, and compared for each line. The lower priority “E” and “F” tags were binned for Caribou-Palermo, and were associated with relatively minor corrective actions such as missing signage, loose bolts, or bent secondary members of the steel frame. Comparison line “E” and “F” tags were tallied but not binned, as our analysis was focused on higher priority / risk issues associated with “A” and “B” tags.

Line Comparison and Normalization Methodology

To best compare lines of different lengths with different numbers of structures, tag counts were normalized by the number of steel lattice towers based on approximations from PG&E’s GIS data. This eliminated the majority of wood poles, steel poles, and other structure types, and made comparison between lines of different lengths more accurate. To further refine the comparison, steel lattice towers over 1,000 feet were used as an approximation of the transition from double- to single-circuit towers. This differentiation allowed a more accurate comparison between Caribou-Palermo north and south sections, as well as with other similar tower constructions.

Caribou-Palermo North and South Designations

For elevations greater than approximately 1,000 feet, PG&E transmission lines typically change from a double-circuit vertical configuration to a single-circuit horizontal configuration (snow towers). The intent of the snow tower configuration is to help minimize the risk of contact between phases during snow loading events. An example of each tower type is shown in Figure 2. For Caribou-Palermo, this transition takes place near the Big Bend substation just north of Lake Oroville (at approximately 1,250 feet), indicated by the dividing line on the map in Figure 3. The north and south portions of this demarcation are designated as Caribou-Palermo North and South throughout the remainder of this report. Historically, these two portions of Caribou-Palermo were two separate lines built at different times and to different specifications. Because the single-circuit snow towers are constructed differently than the standard double-circuit towers, and because the reported Camp Fire incident tower is located on Caribou-Palermo North, specific attention is given to this line section in our analysis. A similar dividing line is made on all comparison lines at the 1,000-foot elevation.

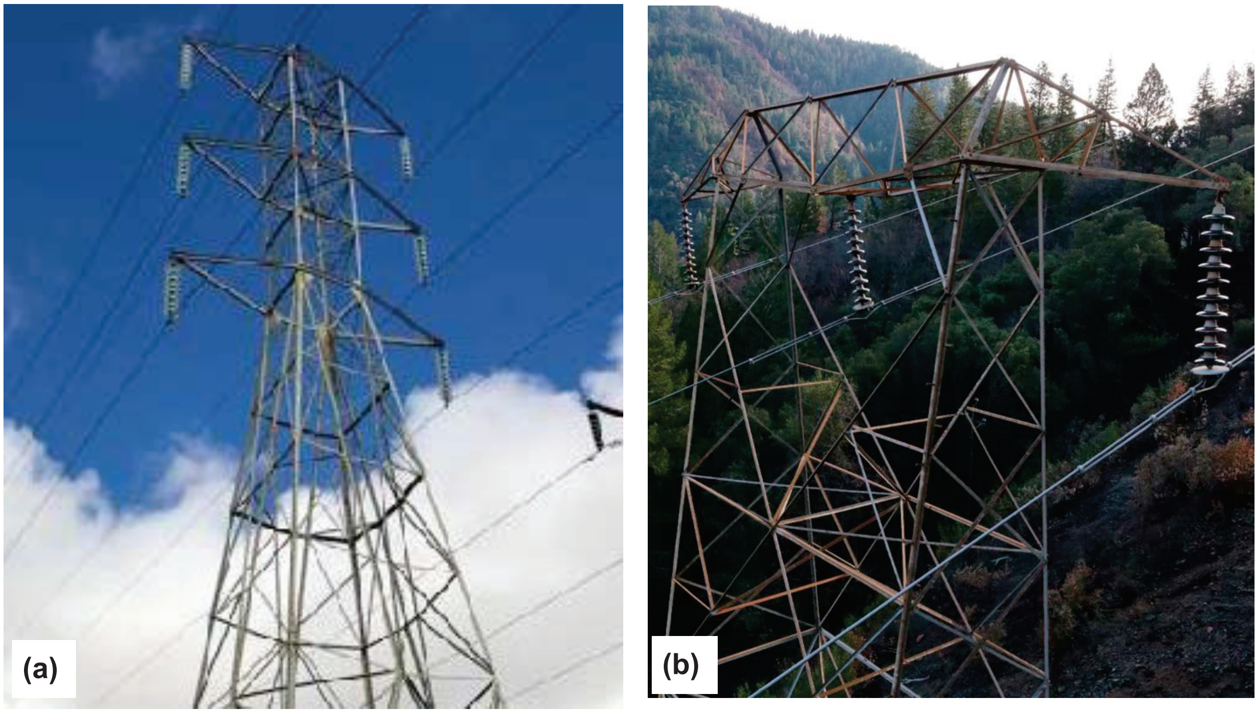


Figure 2. Examples of (a) a double-circuit vertical configuration tower used at elevations below approximately 1,000 feet and (b) a single-circuit horizontal configuration tower used at elevations greater than 1,000 feet.

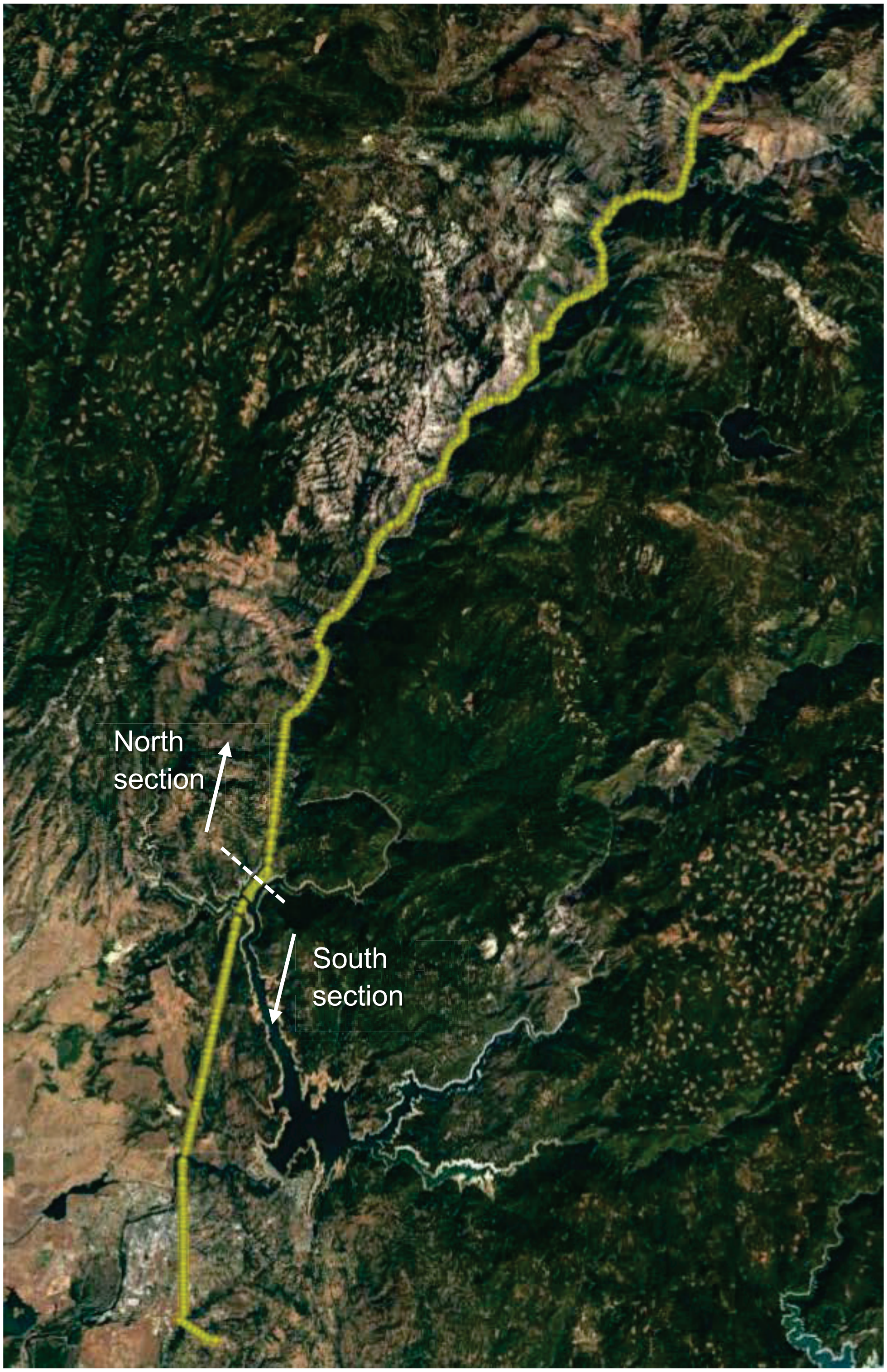


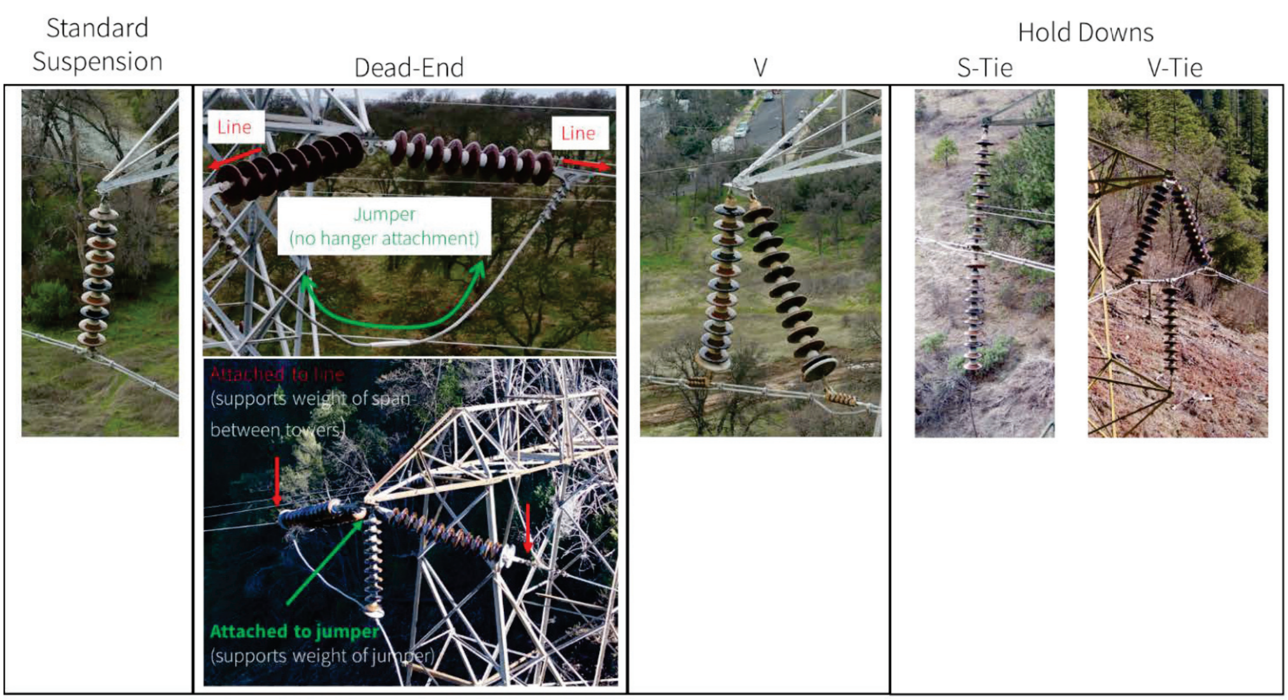
Figure 3. Map of all structures in Caribou-Palermo, with the dividing line between north and south sections indicated.

Hardware Binning

Part of our analysis focused on examining cold-end hardware types and performance on Caribou-Palermo and comparison lines. A variety of cold-end insulator hardware is used to attach insulators to the numerous different tower types. To better understand the specific connection types associated with wear tags, and to compare these to the hardware used on other lines, available drone images from Caribou-Palermo and selected comparison lines (BCRC, CRO, DRO, DH, and PTM) were analyzed. Each insulator-to-tower attachment point was binned into the following categories:

- Insulator configuration (standard suspension, dead-end, V, V-tie, and S-tie)
- Insulator connector type (C-hook, Y-clevis, link, yoke, eye-bolt, or cable)
- Main line or jumper connection
- Tower connection type (hanger plate eye, a shackle, or directly to the tower)
- Tower connection orientation with respect to the conductor (parallel or perpendicular)
- Insulator color and material: porcelain (brown), porcelain (white), polymer, or glass
- Whether the tower is a transposition tower (yes or no)

Examples of the various insulator-tower attachments are shown in Figure 4.



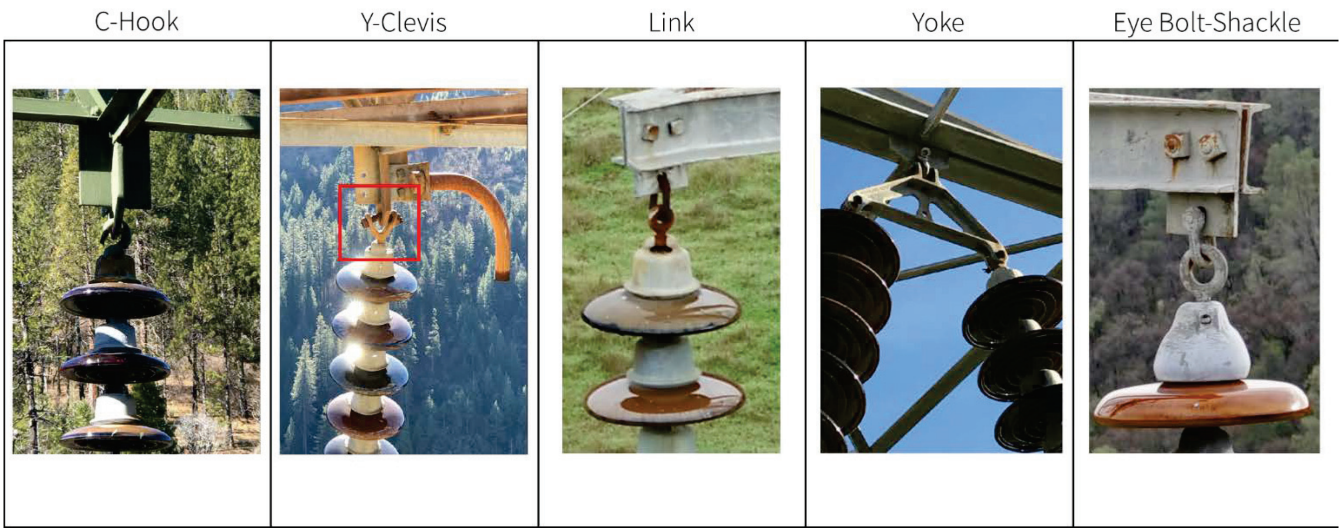


Figure 4. Representative images of insulator configuration (top) and connector type (bottom).

Review of Hardware Specifications and Other Relevant Documentation

Exponent also reviewed line hardware specifications and drawings to help determine whether the Caribou-Palermo and comparison lines had different original design features. Design books from the following lines were included in this investigation:

- Caribou-Golden Gate: 165 kV and 230 kV
- Caribou–Sycamore Creek: 115 kV
- Drum–Rio Oso: 115 kV
- Palermo–Rio Oso: 115 kV

Tower design information from 1916 through the 1980s, including bills of materials, component designs, and geographic line placement, was reviewed. These design books contain information on portions of modern-day Caribou-Palermo and other comparison lines. However, due to hardware replacements, tower relocations, line name changes, and other changes to these lines over time, the extent to which current and specific Caribou-Palermo and comparison towers contain the hardware mentioned in these documents is unknown.

Geographic Considerations for Terrain and Wind

For comparison line mapping, geographic information system (GIS) data of each tower was implemented in Google Earth Pro to generate maps and overlays. Information derived from such

maps for towers includes but is not limited to local terrain, slope, elevation,[1] distance between towers, and mapping references for weather-related data.

For environmental considerations, the National Renewable Energy Laboratory (NREL) Wind Resource database,[2] which combines measured wind data with topographic/meteorological indicators to report wind speed and direction across the United States in one-hour time increments, was utilized. The year 2010 was selected as representative for the hour-by-hour behavior of each tower throughout an entire year, as well as the yearly average.

[1] Some elevations were obtained through GPS Visualizer, https://www.gpsvisualizer.com/elevation, which sources elevation data from the U.S. Geological Survey's National Elevation Dataset.

[2] NREL Wind Database: https://www.nrel.gov/grid/wind-toolkit.html.

Observations and Analysis

Post-Camp Fire Caribou-Palermo Tag Analysis

Post–Camp Fire Caribou-Palermo LC steel lattice tower tags were reviewed and binned by component type and damage mode. Each tag was binned into one of 15 component-type categories:

- *Cold-End Hardware*: Components used to attach the nonconductor end of the insulator (cold-end) to the tower. Both the tower and the insulator attachment components are considered cold-end hardware.
- *Foundation*: Components associated with the footings at the tower base.
- *Bolts*: Fasteners within a structure, typically in the steel frame.
- *Conductor*: The components associated with conducting electricity, including the conductor itself, as well as splices and jumpers.
- *Steel Frame*: The structural steel members of a lattice tower.
- *Insulator*: The insulating components associated with attaching a conductor to a structure, typically strings of porcelain, glass, or plastic discs. For our purposes, the insulator does not include the hardware used to attach insulator strings to a conductor or to a tower.
- *Cotter Pin*: Pinned fasteners, typically in the shoe that connects a suspended conductor to an insulator string.
- *Shoe*: The component used to attach an insulator string to a suspended conductor.
- *Guy*: Guy lines, including guy anchors and strain insulators.
- *Corona Ring*: Rings used to prevent corona discharge at insulators.
- *Clamps*: Attachments to a conductor or hold-down hardware.
- *Signage*: Signage on a tower, including tower number signs, high-voltage signs, and anticlimbing guards.
- *Turnbuckle*: Tensioning apparatus typically in guy line or hold-down cable attachments.
- *Armor Rod*: Hardware that protects conductors from bending, compression, or abrasion.

- *Unclear*: For some tags, information recorded in the tag data was insufficient to determine the associated component type; these tags were binned as "Unclear."

The number of post–Camp Fire Caribou-Palermo "A" and "B" tags associated with each of the 15 component type categories is shown in Figure 5(a). Cold-end hardware accounted for the highest number of "A" tags, as well as the second highest number of "B" tags. Tower foundations were associated with the highest number of "B" tags but no "A" tags. Notably, these two component types combined account for nearly four times the number of high-priority tags of the next most tagged component, and approximately half of all high-priority tags. In Figure 5(b), the distribution of component type categories is shown only for high-priority tags from steel lattice towers on Caribou-Palermo North.

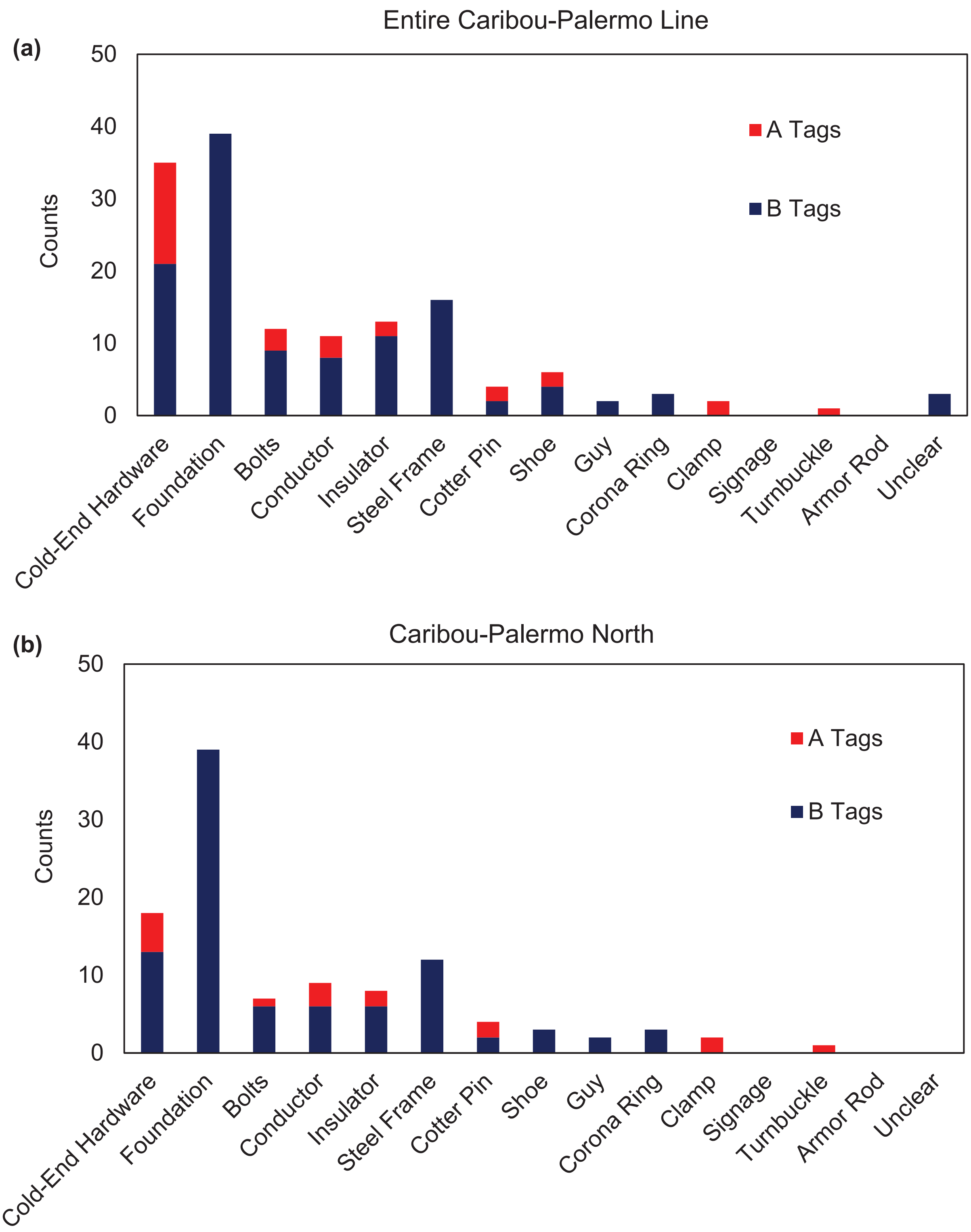


Figure 5. Breakdown of post–Camp Fire high-priority ("A" and "B") tags with respect to component type on (a) entire Caribou-Palermo line and (b) Caribou-Palermo North. (Tags are associated with single-circuit structures north of Tower 016/130.)

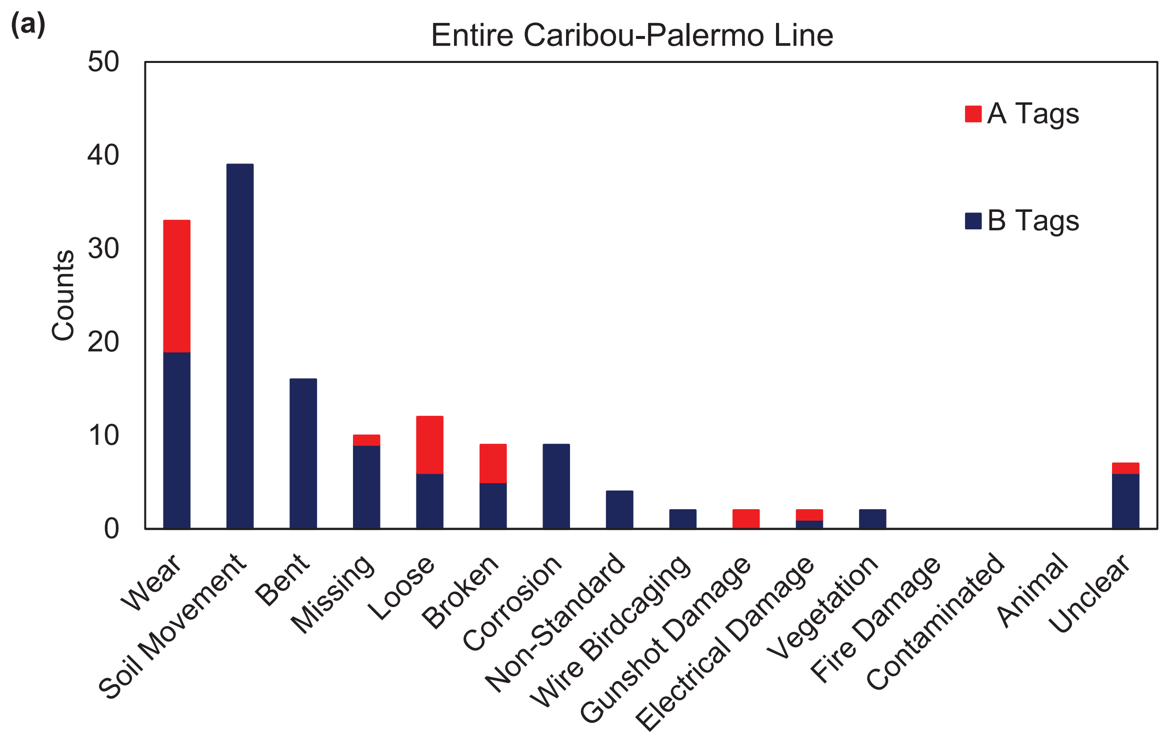
Analysis of High-Priority Tag Damage Mode

In addition to binning of tags by component (described above), each tag was also binned into one of 16 damage mode categories:

- *Wear*: Tags associated with worn components. This category includes material loss due to friction between moving components as well as material loss from tower footings.
- *Soil Movement*: Tags associated with burial or exposure of structure components due to soil movement, typically related to tower footings or guy anchors. Further inspection may be required to assess if soil movement has resulted in a damage condition.
- *Bent*: Tags associated with bent or warped components.
- *Missing*: Tags associated with missing components, most commonly fasteners such as bolts and cotter pins.
- *Loose*: Tags associated with loose components, most commonly fasteners such as bolts and cotter pins.
- *Corrosion*: Tags associated with corrosion of metal components.
- *Broken*: Tags associated with fractured components.
- *Non-Standard*: Tags associated with components that may be in good physical condition but are improperly installed or are otherwise not compliant with standards. For example, tags associated with guy lines installed without strain insulators or splices installed less than the required 10 feet from a tower were included in this category.
- *Wire Birdcaging*: Tags associated with unraveling of the strands of a conductor.
- *Gunshot Damage*: Tags associated with components likely damaged by gunshots.
- *Electrical Damage*: Tags associated with electrical damage to components, including arcing or tracking damage on insulators, as well as lightning strikes.
- *Vegetation*: Tags associated with vegetation that poses risk to a structure, including branches on or near conductors and excessive vegetation around the base of a tower.
- *Fire Damage*: Tags associated with components damaged by fire.
- *Contaminated*: Tags associated with contamination on a component, such as paint or bird droppings on an insulator.
- *Animal*: Tags associated with damage or risk to a structure related to animals, such as bird nests or woodpecker holes.

- *Unclear*: For some tags, information recorded in the tag data was insufficient to determine the associate damage mode; these tags were binned as "Unclear."

The number of "A" and "B" tags from Caribou-Palermo associated with each of the 16 damage mode categories is shown in Figure 6(a). The distribution of high-priority tags among damage mode categories closely parallels their distribution among component types. Wear tags are primarily associated with cold-end hardware, and soil movement is associated with foundations. These two damage modes represent the highest numbers of "A" and "B" tags, respectively, and, combined, account for more than four times the number of high-priority tags of any other damage mechanism. Tagged component breakdowns on Caribou-Palermo North are shown in Figure 6(b).



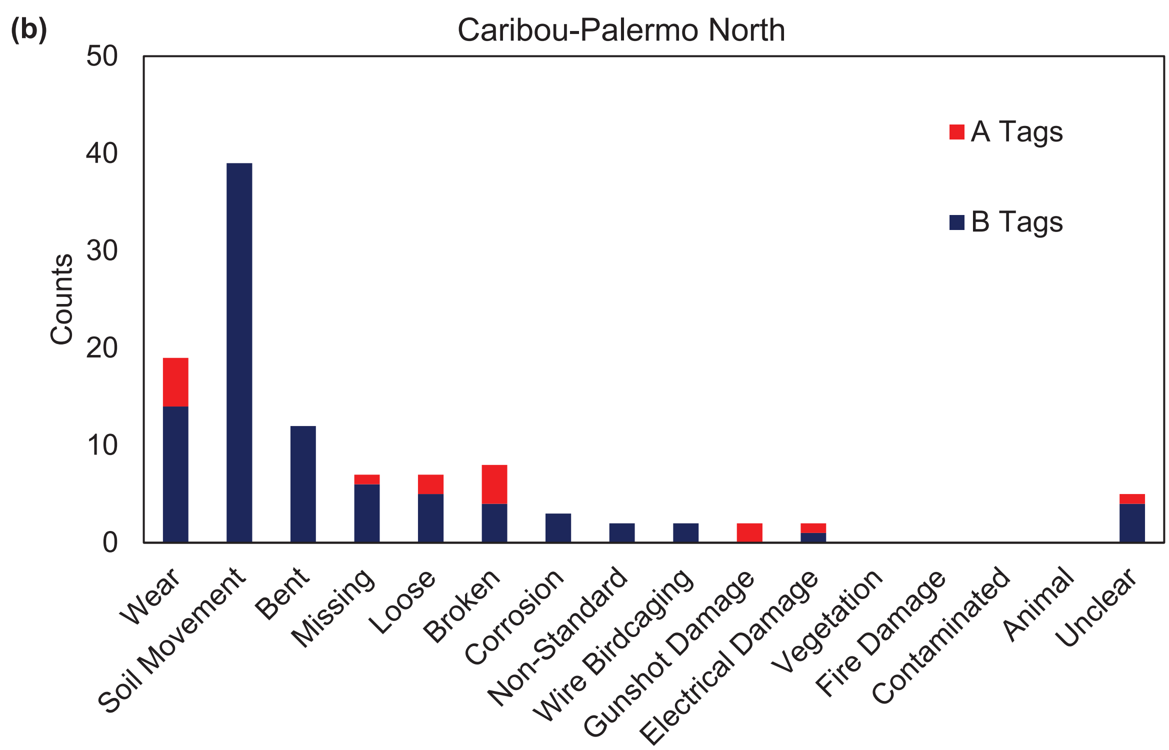


Figure 6. Breakdown of post–Camp Fire high-priority (“A” and “B”) tags with respect to damage mode on (a) entire Caribou-Palermo line and (b) Caribou-Palermo North. (Tags are associated with single-circuit structures north of tower 016/130.)

A breakdown of the damage modes associated with selected component types, Figure 7, indicates that cold-end hardware tags were almost exclusively associated with wear. Similarly, all foundation tags were associated with soil movement. We note that while soil movement may pose risk to the structural integrity of tower foundations, further inspection is required to assess whether soil movement actually resulted in damage to any components. A closer examination of both cold-end hardware / wear tags and foundation/soil movement tags is provided in the following section.

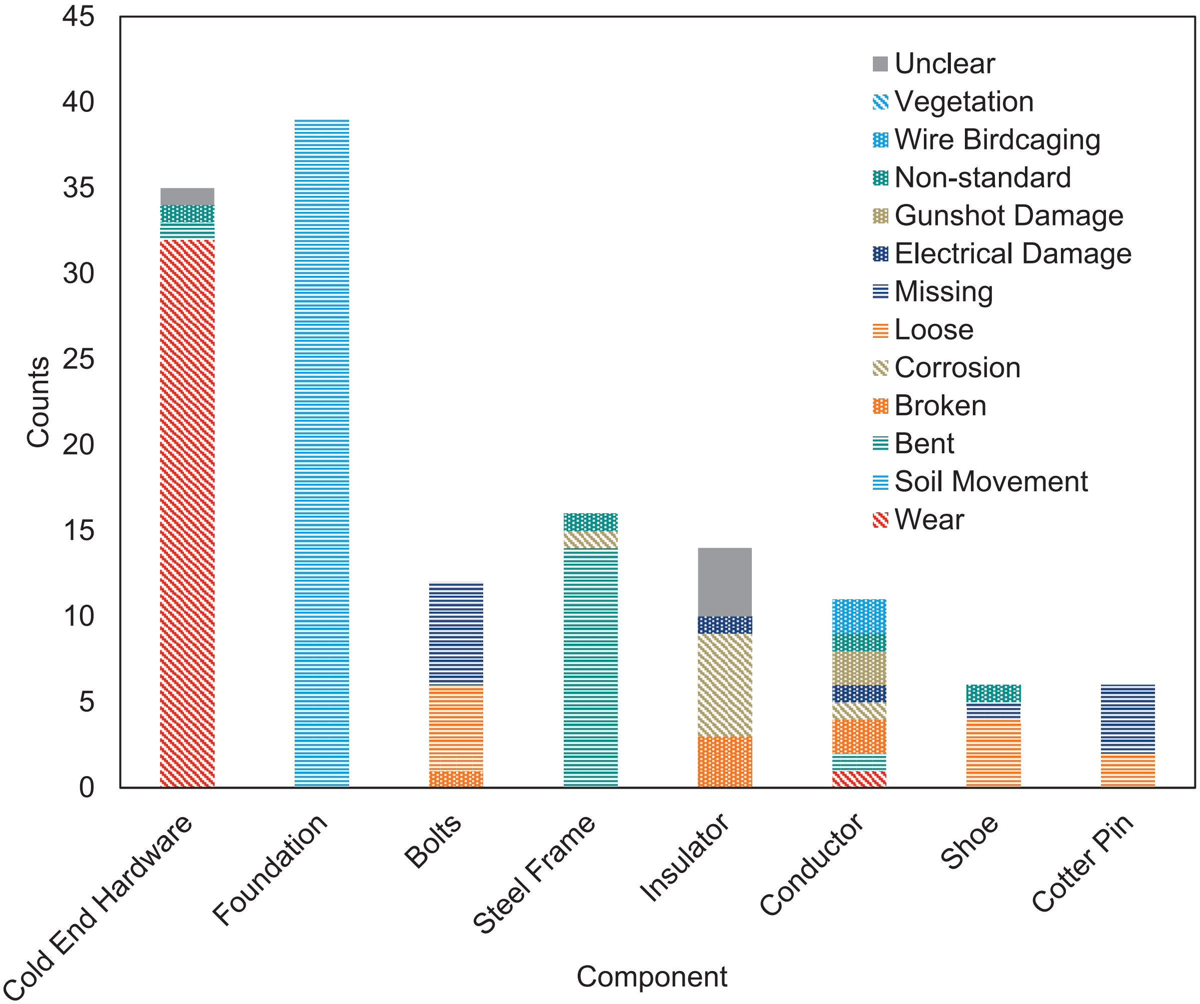


Figure 7. Breakdown of post–Camp Fire Caribou-Palermo high-priority tags by component type and damage mode.

Cold-End Hardware and Foundation Tags

"Cold-end hardware" in this report refers both to the connector (e.g., link, c-hook, y-clevis, etc.) attached to an insulator string and to the hanger plate or shackle on the tower to which the connector attaches. Repeated relative motion between the connector and the eye of the hanger plate (or shackle) gradually wears away material from both. Photographs of cold-end hardware wear are shown in Figure 8, evidenced by the elongation of initially circular hanger-plate eyes. Over time, reduced thickness of the connector and hanger-plate from cumulative wear can result in strength reduction of both components.

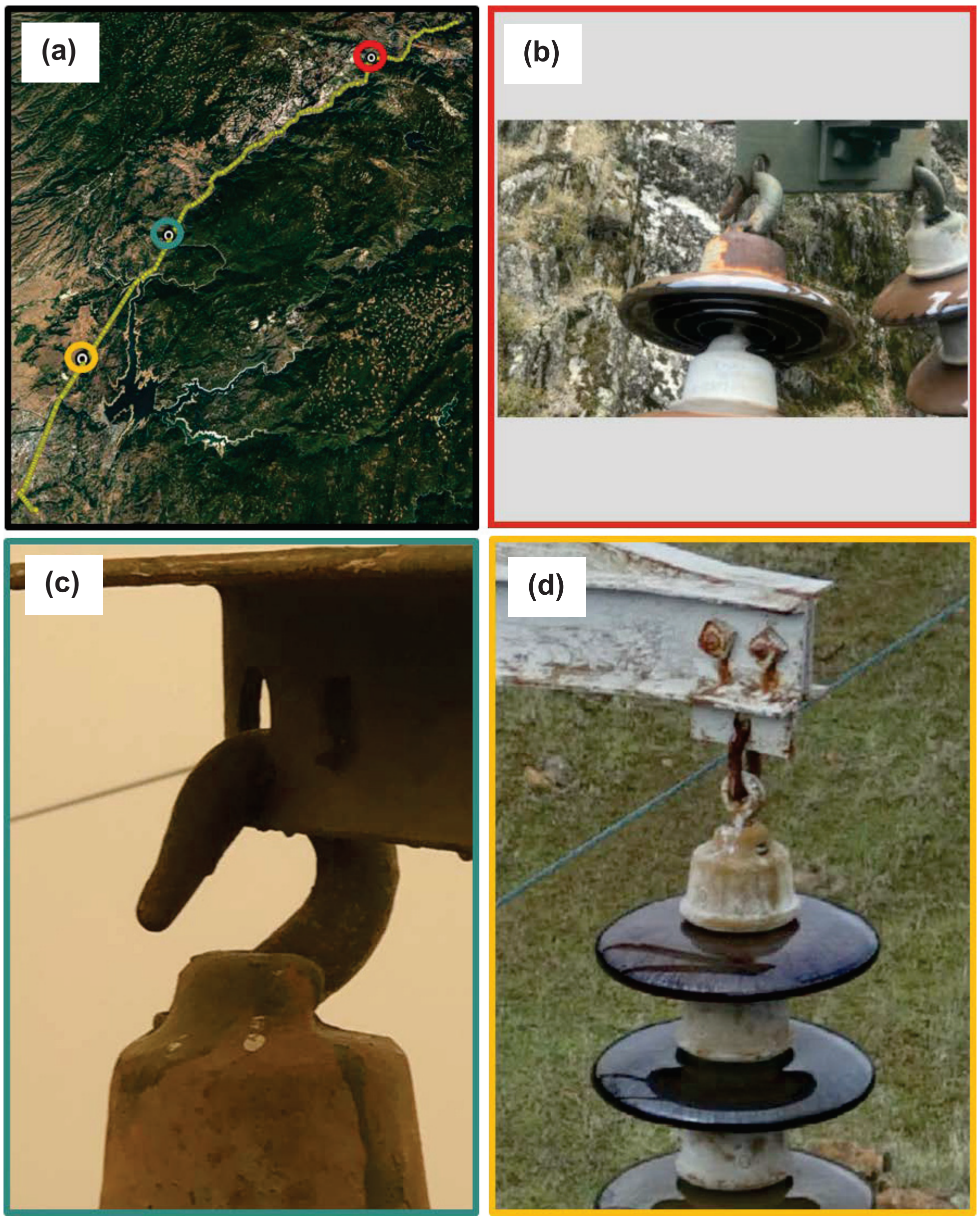


Figure 8. Representative photographs of cold-end hardware wear associated with high-priority tags at the locations marked in (a), for (b) northern segment of the Caribou-Palermo line (SAP# 40910322), (c) middle of the line (SAP# 40591574), and (d) the southern region of the line (SAP# 40689950).

Representative photographs of soil movement around tower foundations that led to post–Camp Fire high-priority "B" tags on Caribou-Palermo are shown in Figure 9. For the three examples shown, tags were generated due to burial of the tower footings or steel lattice members. This type of soil coverage can increase the risk of corrosion of buried steel components. However, unlike wear, soil movement does not necessarily represent tower damage. Further assessment would be required to determine if soil movement associated with high-priority tags resulted in damage.

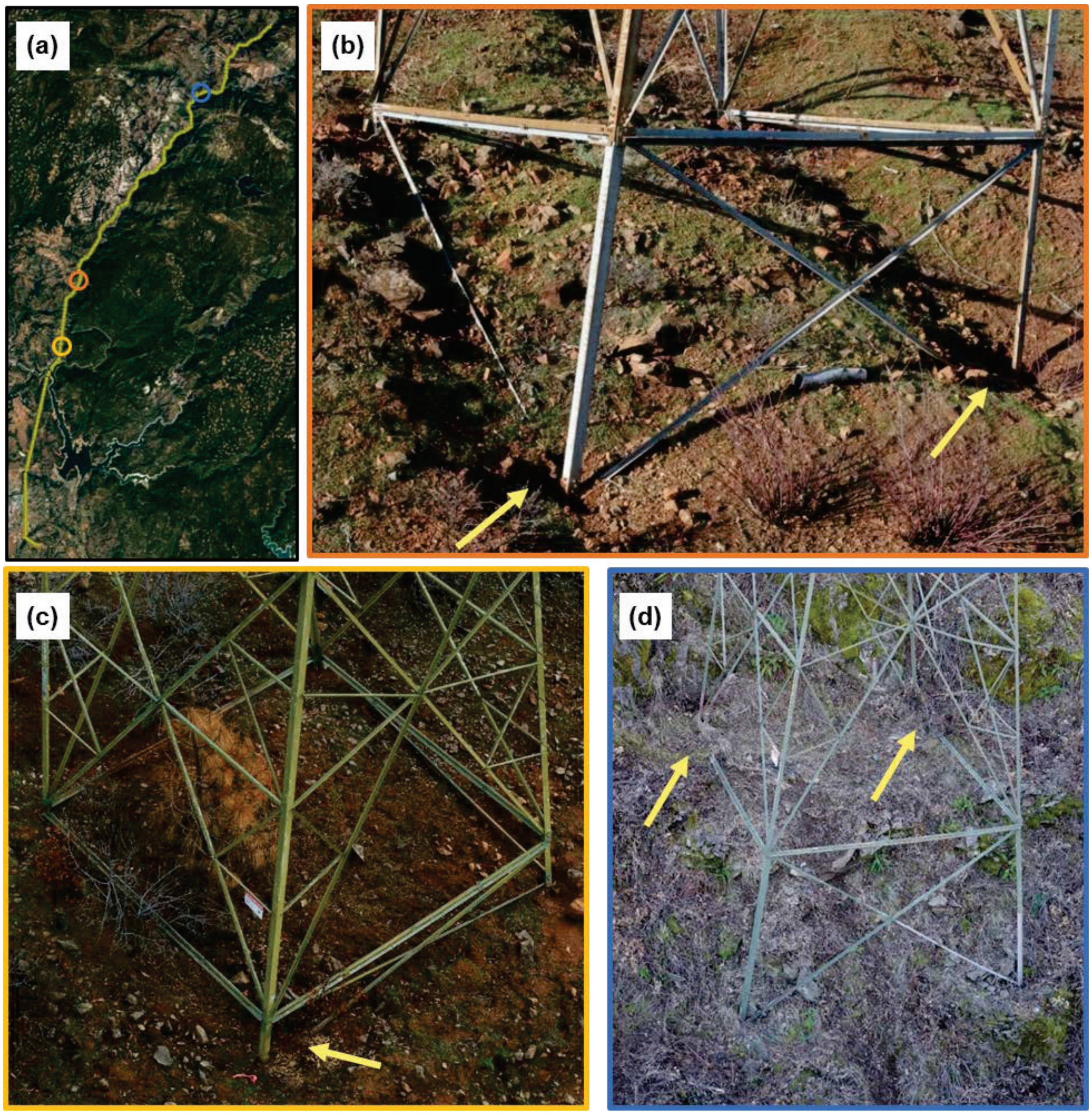


Figure 9. Representative photographs of soil movement around tower foundations associated with high-priority tags on Caribou-Palermo at the locations marked in (a), for (b) SAP# 40770937, (c) SAP# 40599306, and (d) SAP# 40910316.

No apparent correlation was found between cold-end hardware and foundation tags. The locations of high-priority tags associated with cold-end hardware / wear or foundation/soil movement are mapped in Figure 10. The majority of the foundation/soil movement tags were clustered just north of Lake Oroville. Cold-end hardware / wear tags were distributed along the length of Caribou-Palermo, both north and south of Lake Oroville.

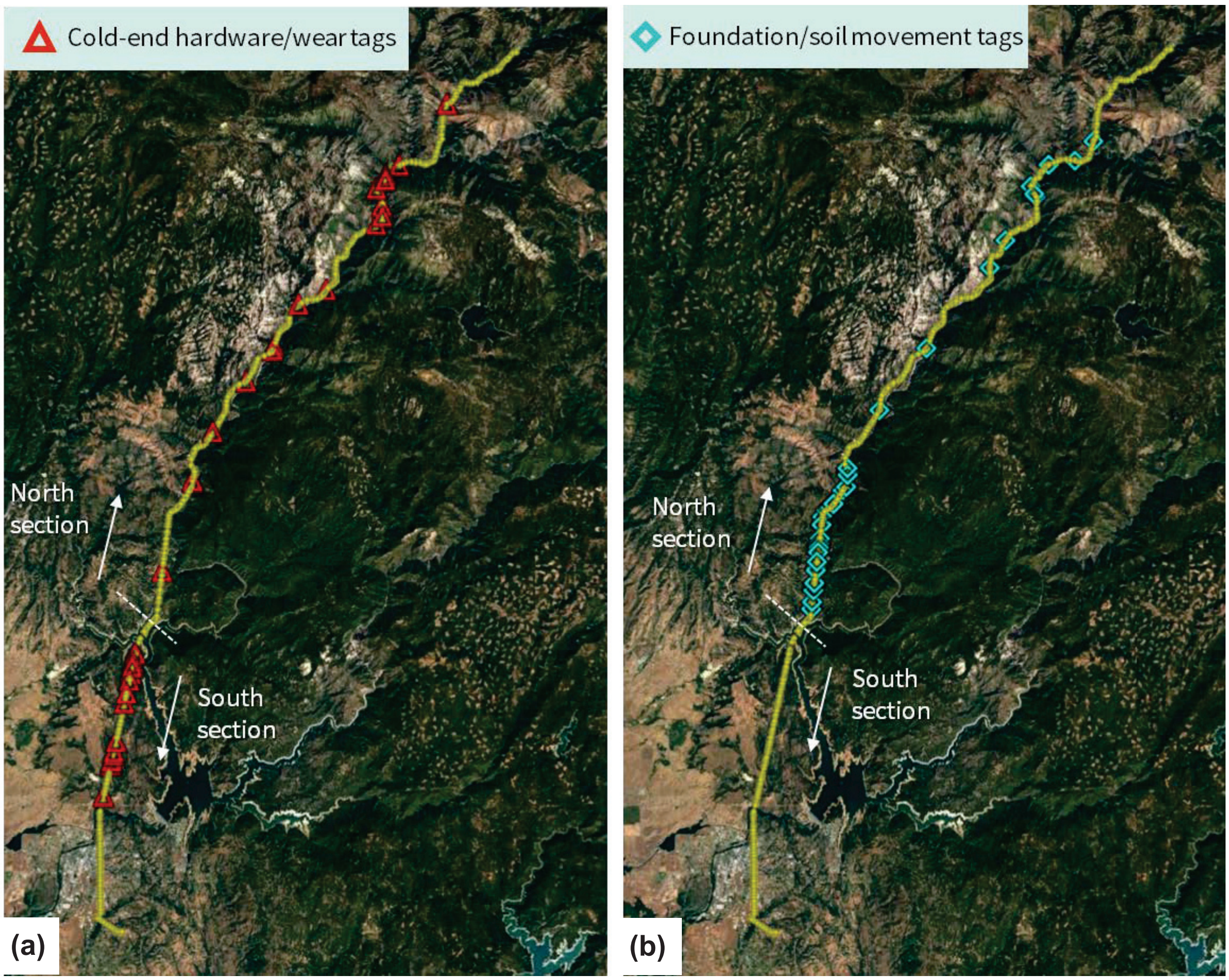


Figure 10. Maps of post–Camp Fire high-priority (a) cold-end hardware / wear tags and (b) foundation/soil movement tags on Caribou-Palermo.

Comparison Line Post-Camp Fire Tag Analysis

A similar tag binning analysis was conducted on the full set of 28 comparison lines. All WSIP "A" and "B" tags from November 9, 2018, to June 19, 2019, were reviewed and binned into the component and damage mode categories described above.

Figure 11(a) compares the overall high-priority tag count between Caribou-Palermo and the comparison lines. The Caribou-Palermo line had substantially more high-priority tags than any other comparison line; however, Caribou-Palermo also contained an above-average number of steel lattice towers, and steel lattice towers over 1,000 feet. The overall number of steel lattice towers and steel lattice towers over 1,000 feet (obtained from Google Earth) are shown in Figure 12. The normalized tag count at each priority level for Caribou-Palermo and the other comparison lines is shown in Figure 13.

The Caribou-Palermo line exhibited a higher normalized high-priority ("A" + "B") post–Camp Fire tag count than all other comparison lines, as shown in Figure 13. Furthermore, three of the four lines with the next highest normalized tag counts are located adjacent to Caribou-Palermo in (or near) the North Fork Feather River Canyon: Bucks Creek–Rock Creek–Cresta (BCRC), Paradise–Table Mountain (PTM), and Cresta–Rio Oso (CRO).

The portion of the PTM line which extends southward from the Big Bend substation (just north of Lake Oroville) was originally part of the Caribou-Valona line. This line was installed in 1921 and contains similar towers to Caribou-Palermo North with respect to design, vintage, and conductor type. Although this portion of PTM contains similar towers to Caribou-Palermo North, fewer high-priority tags were created, as shown in Figure 11. Upon normalizing by the number of steel lattice towers, the number of high-priority tags on PTM is closer to the Caribou-Palermo count, though still lower, as shown in Figure 13. The smaller number of high-priority tags may be due to the fact that this portion of PTM is at lower elevation with lower wind speeds compared to Caribou-Palermo North, as shown in the Environmental Conditions section of this report.

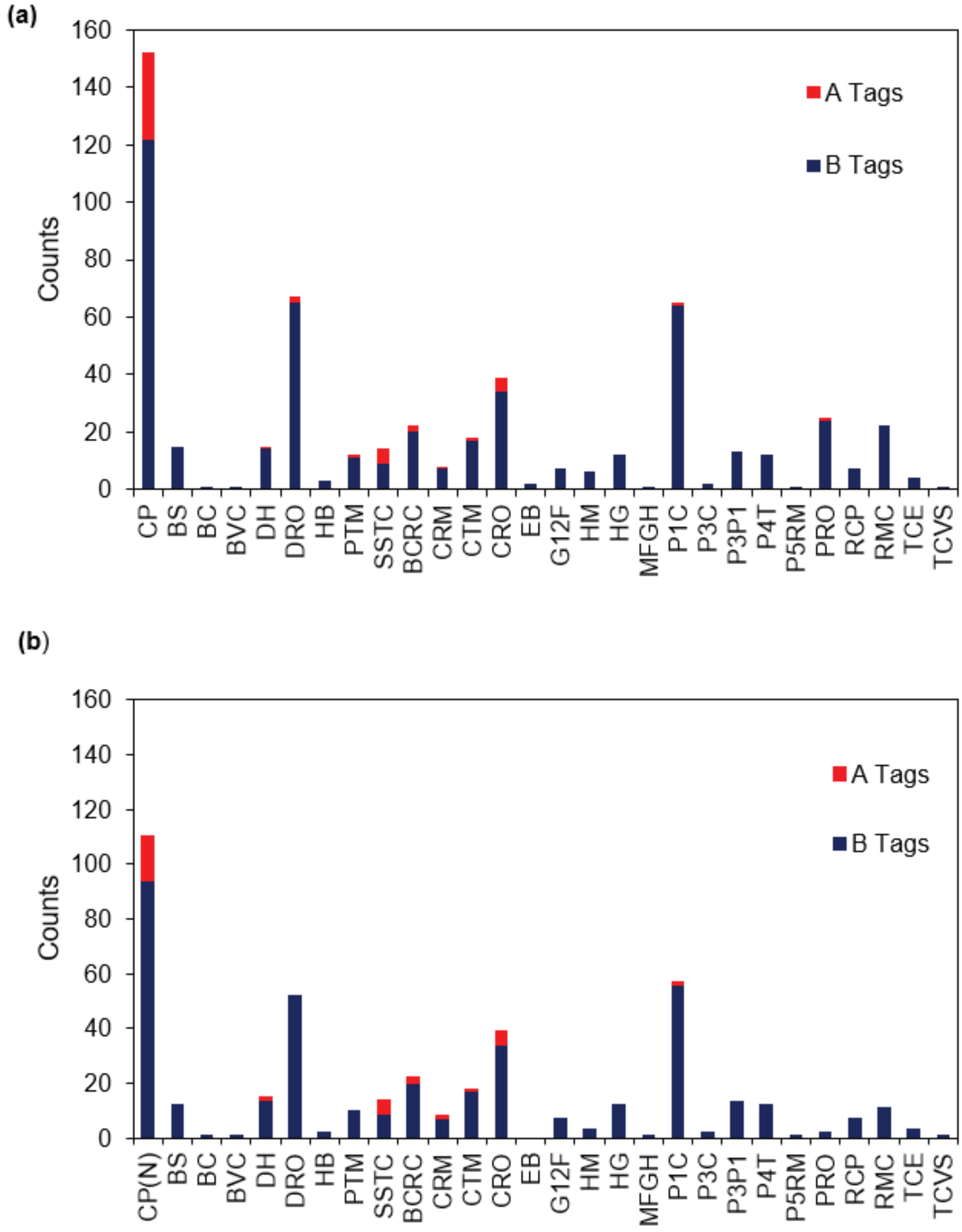


Figure 11. Total post–Camp Fire tag count for Caribou-Palermo and comparison lines on (a) all steel lattice towers, and (b) all steel lattice towers above 1,000 feet.

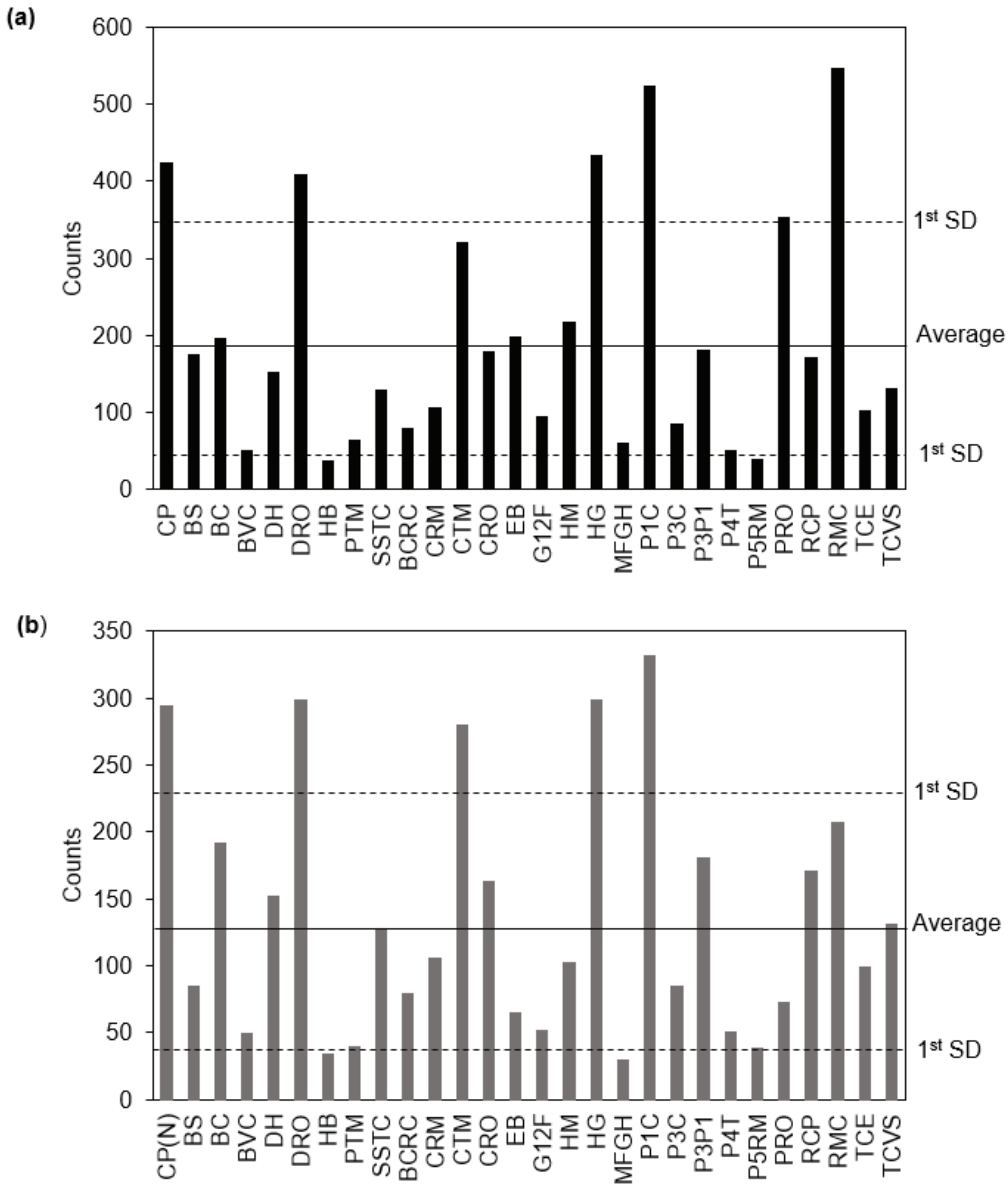


Figure 12. Total counts of (a) all steel lattice towers and (b) all steel lattice towers over 1,000 feet on Caribou-Palermo and comparison lines. The double-to-single circuit transition is estimated at 1,000 feet for all lines except Caribou-Palermo. SD is standard deviation.

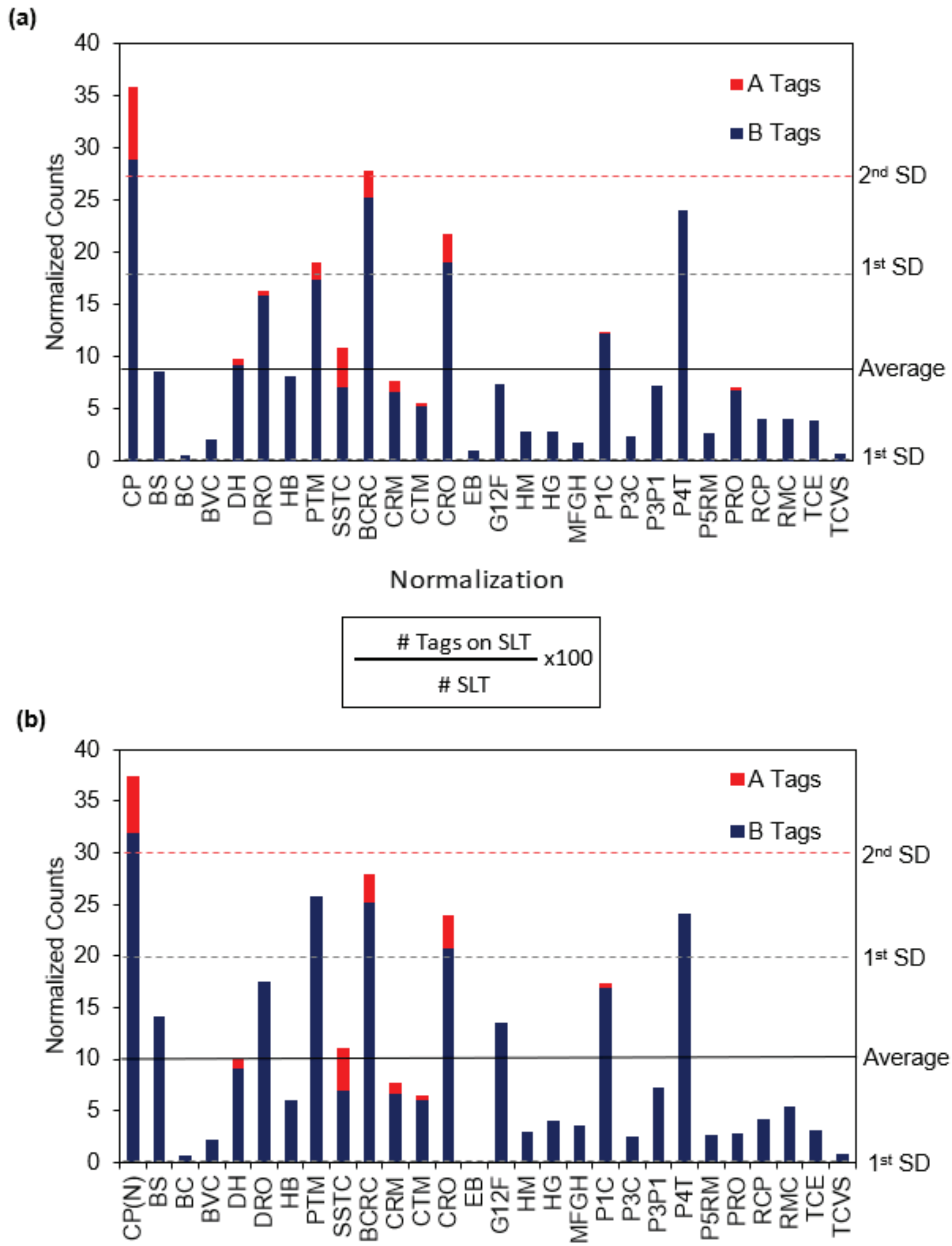


Figure 13. Normalized post–Camp Fire tag rate for Caribou-Palermo North (CP(N)) and comparison lines considering (a) steel lattice towers, and (b) steel lattice towers above 1,000 feet. SLT is steel lattice tower, SD is standard deviation.

Cold-End Hardware Tag Comparison

Figure 14 shows the counts of post–Camp Fire "A" and "B" tags associated with cold-end hardware on all comparison lines. The absolute count of cold-end hardware tags on Caribou-Palermo greatly exceeds that of any other comparison line; however, after normalizing by the number of steel lattice structures in each line, two other lines, Bucks Creek–Rock Creek–Cresta (BCRC) and Cresta–Rio Oso (CRO), are found to have comparable normalized counts of cold-end hardware tags, shown in Figure 15. These three lines, all located in the North Fork Feather River Canyon, exhibit significantly more post–Camp Fire cold-end hardware / wear tags than any of the other comparison lines. Examples of cold-end hardware / wear are shown in Figure 8.

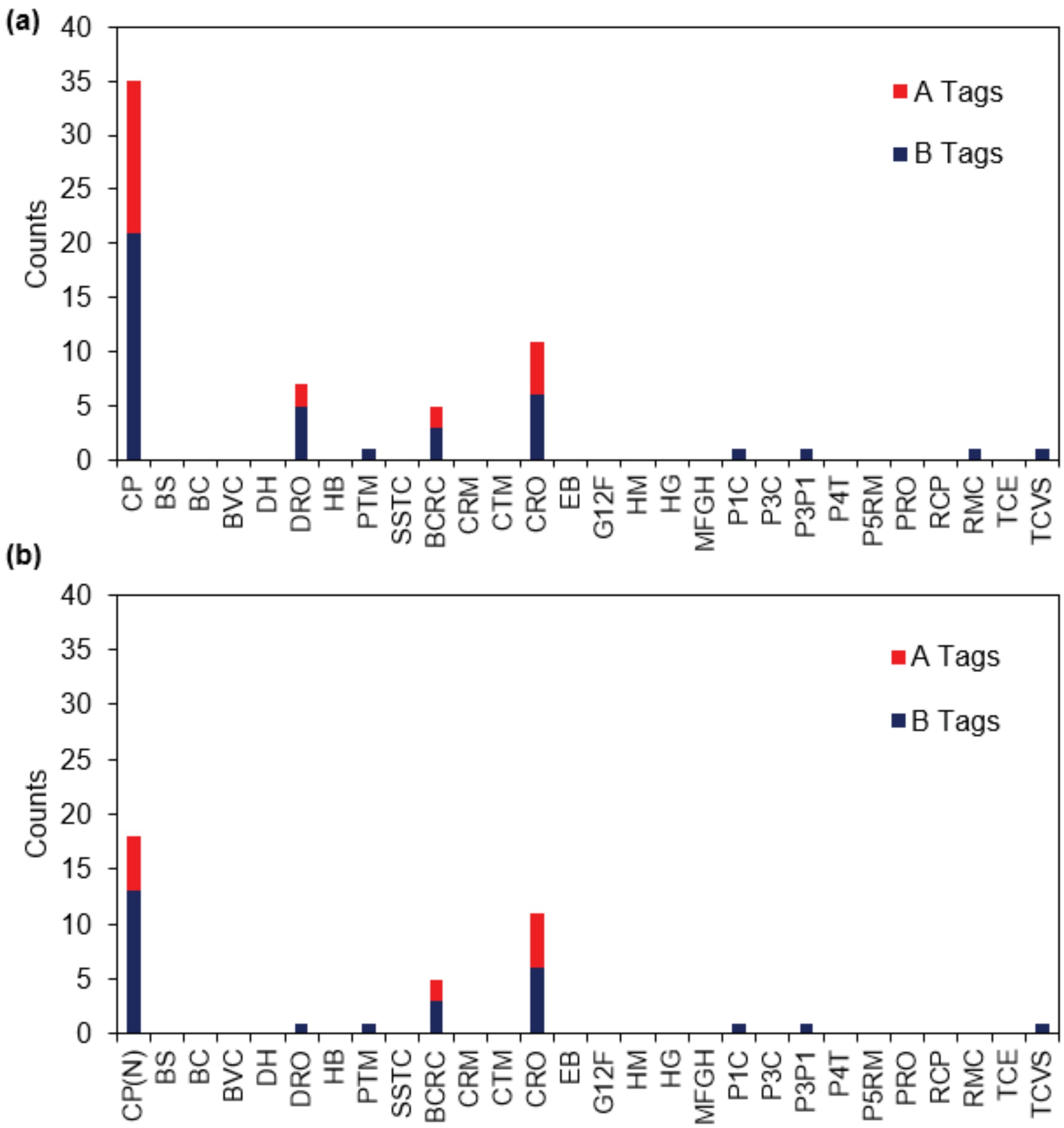
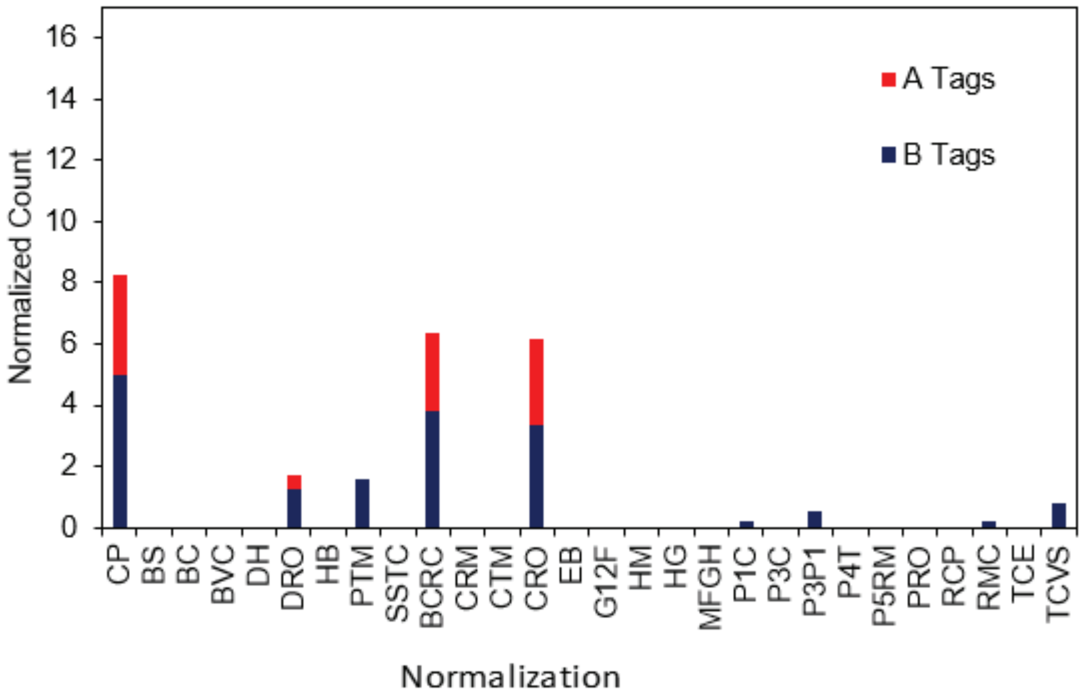


Figure 14. Total counts of post–Camp Fire cold-end hardware tags for Caribou-Palermo (CP) and comparison lines for (a) steel lattice towers and (b) steel lattice towers over 1,000 feet of elevation.

(a)



$$\frac{\#\ \text{Tags on SLT}}{\#\ \text{SLT}} \times 100$$

(b)

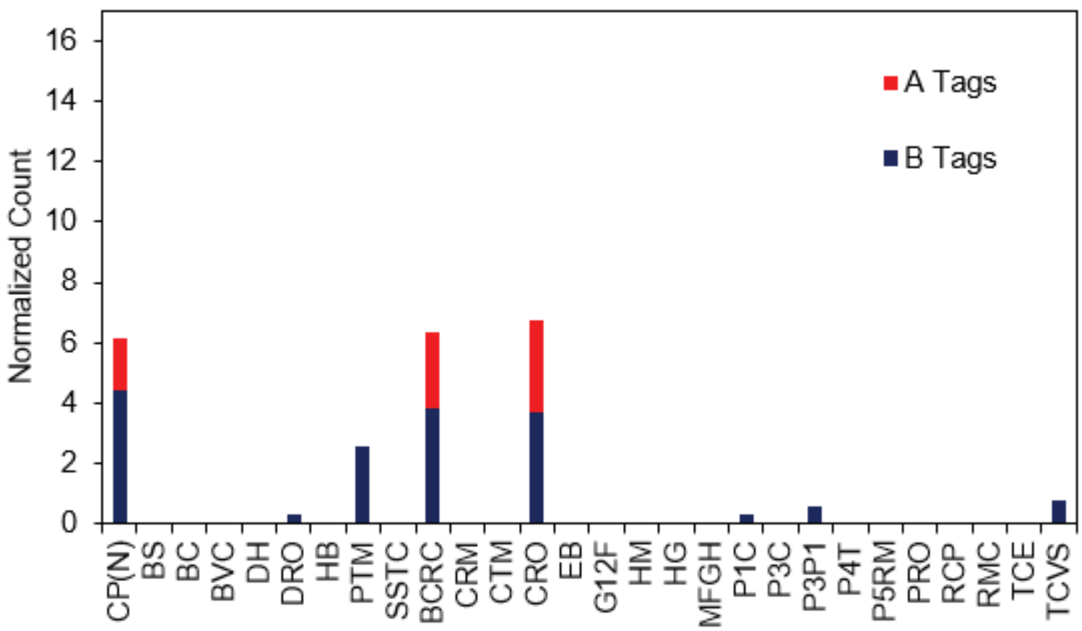


Figure 15. Normalized post–Camp Fire cold-end hardware tag counts for Caribou-Palermo (CP) and comparison lines for (a) steel lattice towers and (b) steel lattice towers over 1,000 feet of elevation. SLT is steel lattice tower.

Foundation Tag Comparison

The most common Caribou-Palermo high-priority "B" tag was associated with buried foundations. Although Caribou-Palermo had roughly twice the number of buried foundation tags as the next highest comparison line, when normalized for the number of steel lattice towers Caribou-Palermo had a comparable number of foundation tags to other lines in the North Fork Feather River Canyon such as Bucks Creek–Rock Creek–Cresta (BCRC) and Cresta–Rio Oso (CRO), as shown in Figure 16.

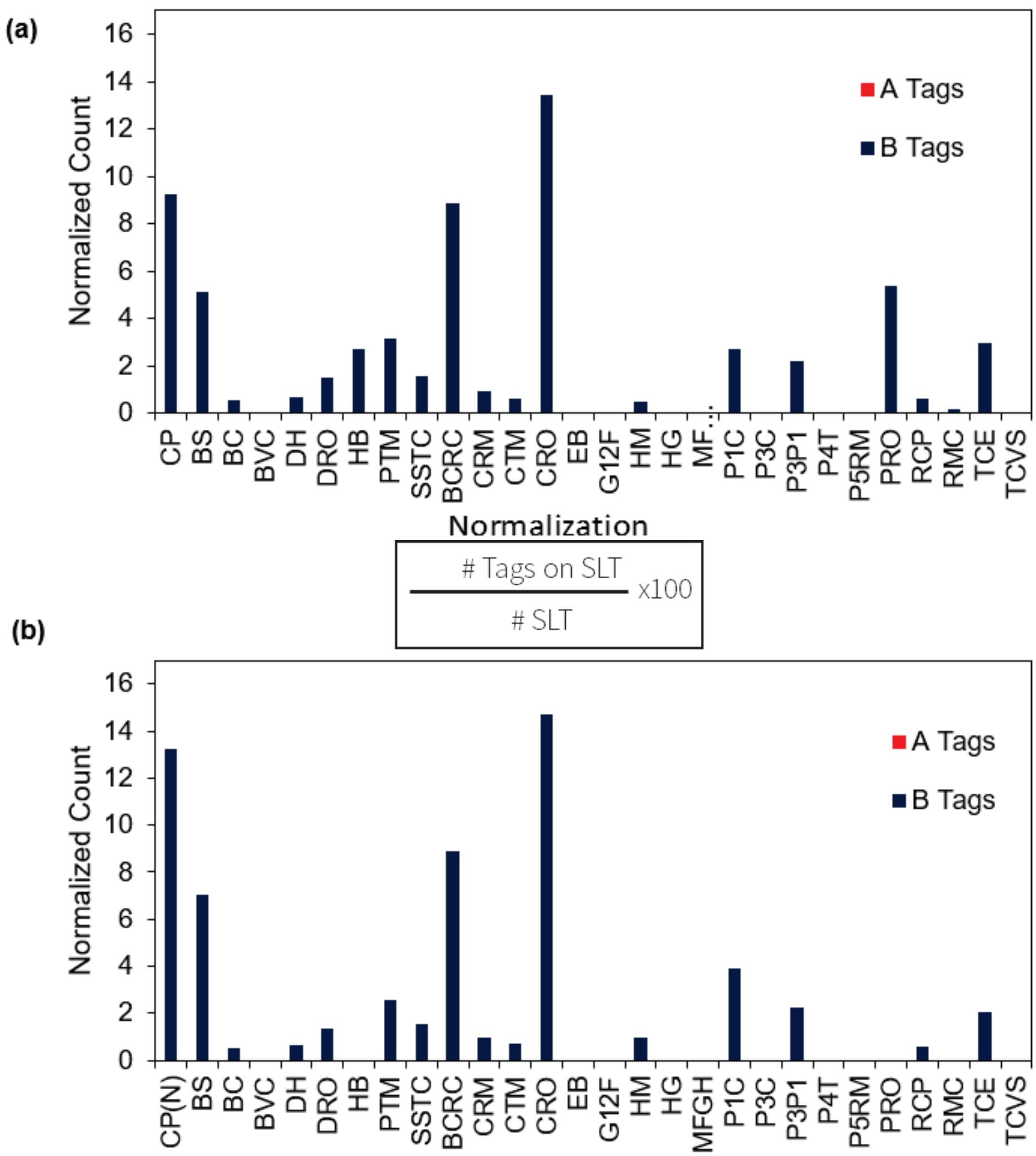


Figure 16. Normalized count of tags associated with foundation tags for Caribou-Palermo (CP) comparison lines for (a) steel lattice towers and (b) steel lattice towers over 1,000 feet of elevation. SLT is steel lattice tower, SD is standard deviation.

Post–Camp Fire Hardware Analysis

Connection Type

Available drone photos were used to determine the type of cold-end insulator hardware on each Caribou-Palermo tower, as well as selected available comparison lines as described in the methodology section. More than 4,000 insulator attachment points were categorized on Caribou-Palermo, CRO, DH, DRO, PTM, and BCRC lines. The numbers of each connection type on Caribou-Palermo South and on Caribou-Palermo North are shown in Figure 17. This analysis shows that the link style connection was unique to Caribou-Palermo South and was not found on Caribou-Palermo North or any of the comparison lines. Example link connections are shown in Figure 18.

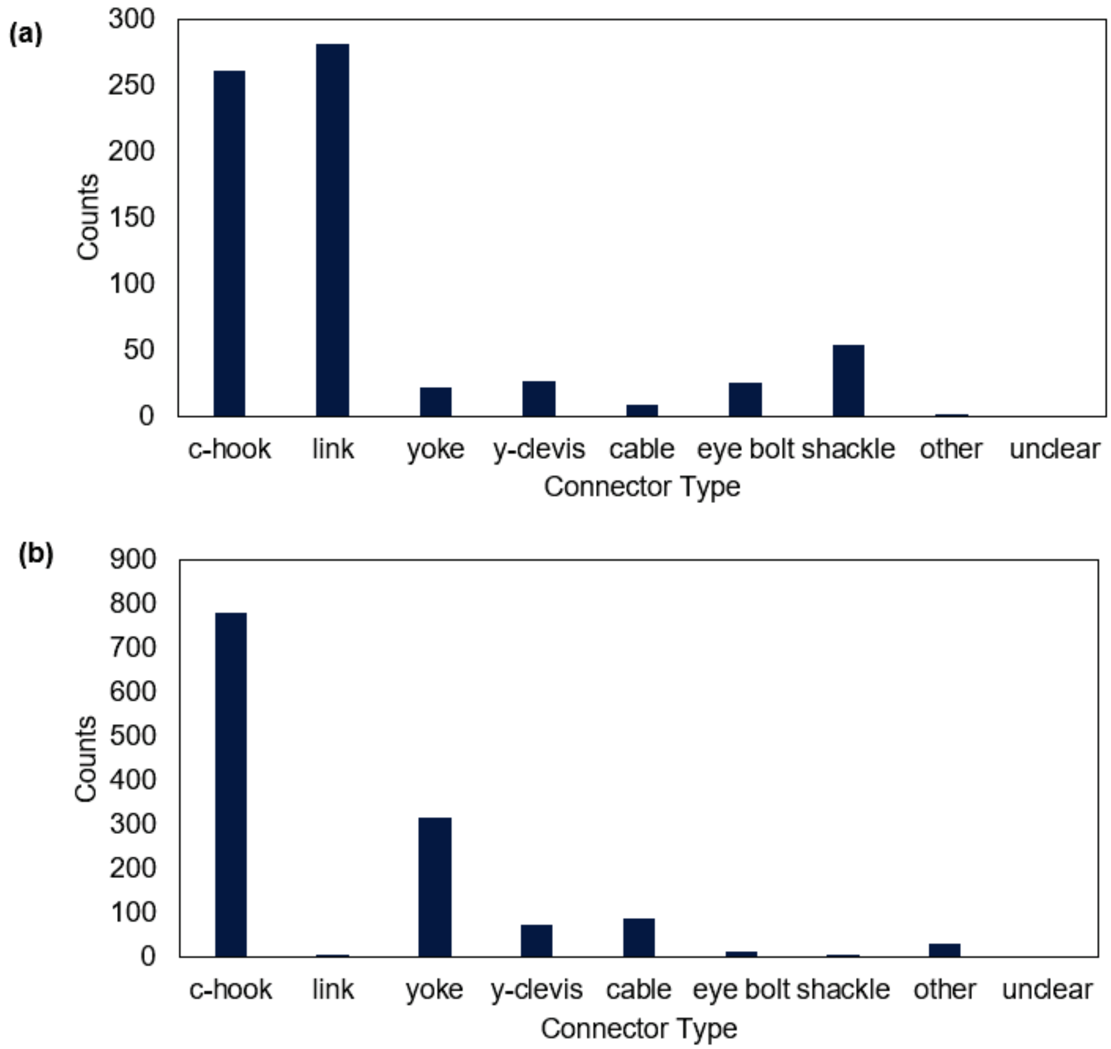


Figure 17. Counts of insulator connection types present on (a) Caribou-Palermo South and (b) Caribou-Palermo North.

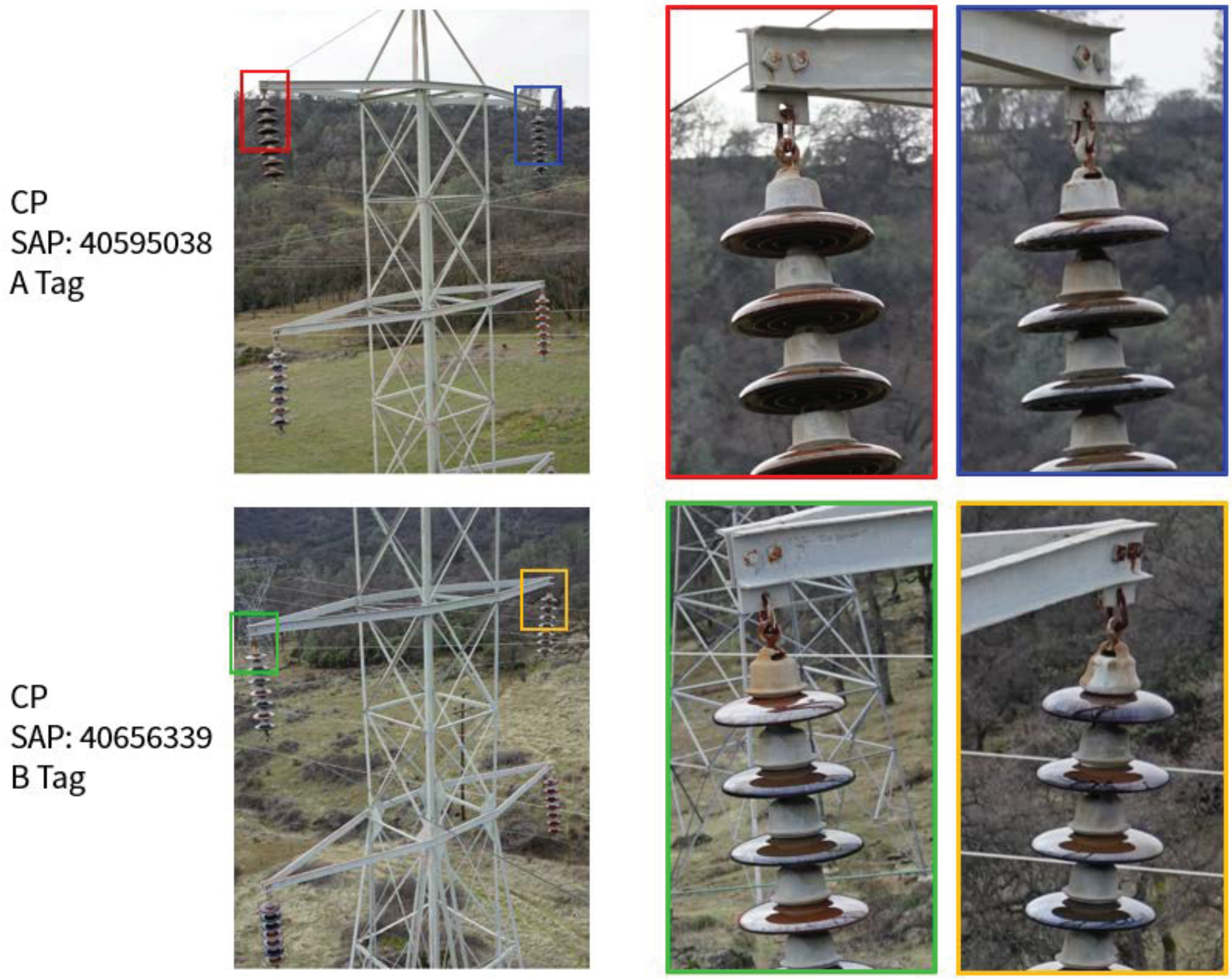


Figure 18. Representative photographs of link connections found on steel lattice towers on Caribou-Palermo South.

Approximately half of the Caribou-Palermo South steel lattice towers contained link connections. However, all of the high-priority Caribou-Palermo South cold-end hardware / wear tags were on structures with link connections (Figure 19). For cases in which a tagged structure contained multiple connection types, the link connection was determined to be the connection likely associated with the wear tag, based on inspector text and photographs of each connection.

Link connections were originally installed on the Great Western Power Company Line #1 (present-day Caribou-Palermo South) as early as 1908.[3] According to design books, both C-hook connections and link connections were utilized in construction of historical transmission lines that included portions of Caribou-Palermo. Technical drawings from these design books indicate that links generally have smaller dimensions than C-hooks (Figure 20), leading to smaller contact area between the connector and the tower attachment point. Distribution of load

[3] Date determined from conversations with PG&E subject matter expert.

across a smaller area could increase the link wear rate, and may contribute to the higher incidence of cold-end hardware / wear tags associated with links compared to C-hooks on Caribou-Palermo South. A plot of the link connection locations along the length of Caribou-Palermo is shown in Figure 21.

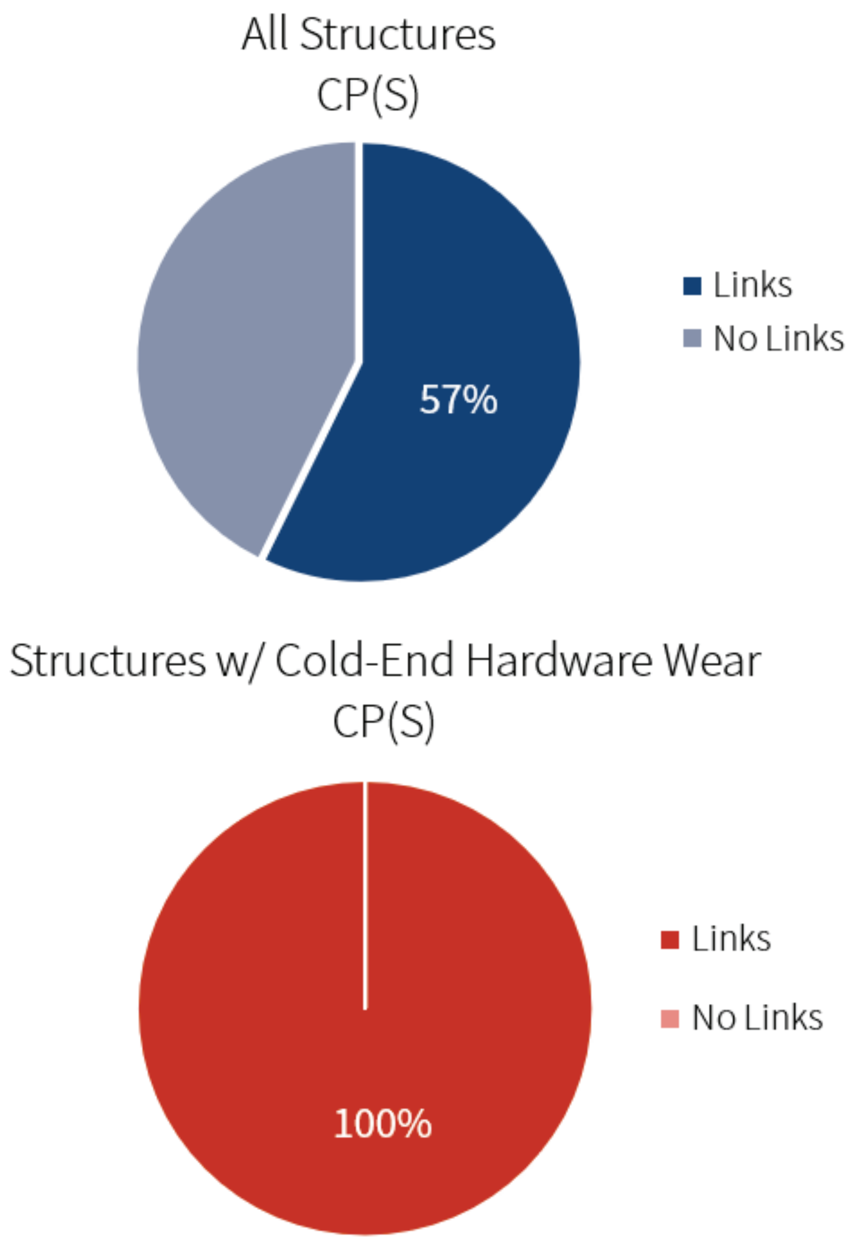


Figure 19. Of the post–Camp Fire drone-inspected steel lattice towers on Caribou-Palermo South, approximately 57 percent contained one or more link connections. However, all 14 of the high-priority cold-end hardware / wear tags on Caribou-Palermo South were on structures with link connections.

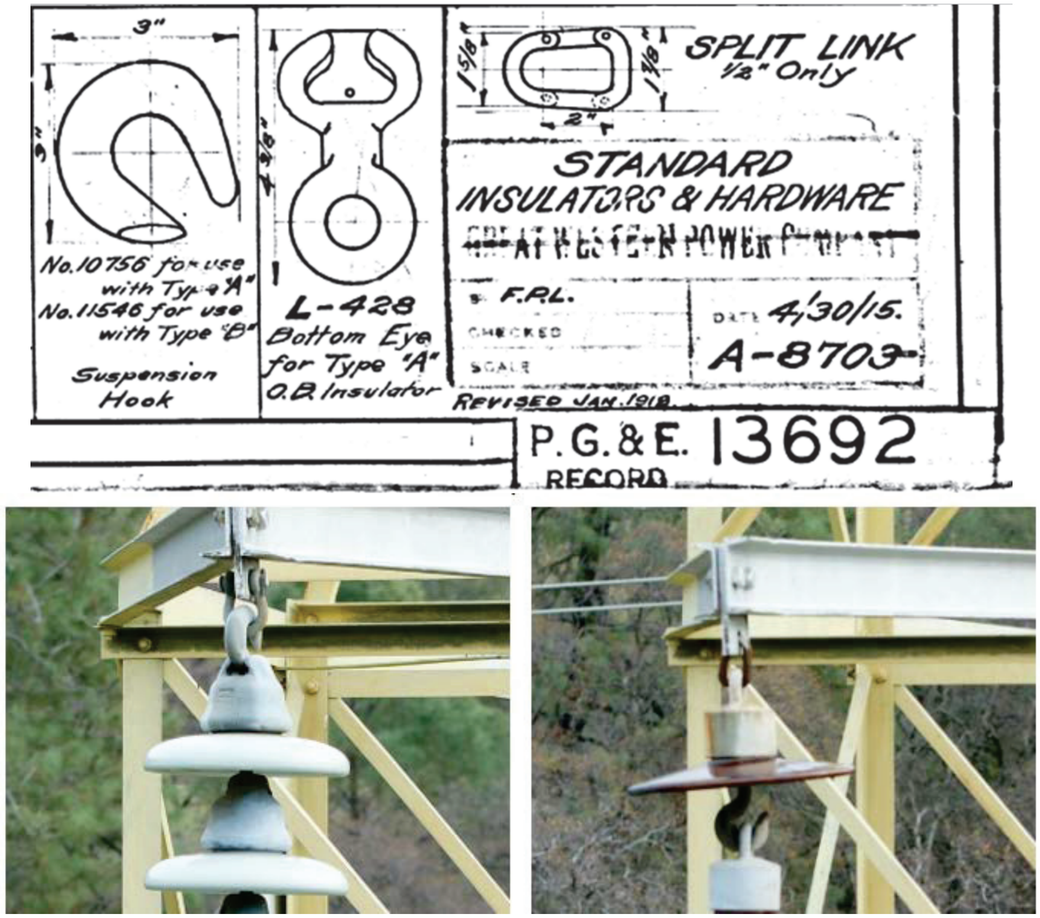


Figure 20. Design book drawing from 1918 showing C-hooks and link connections used during this time (top), and photograph of C-hooks and link connections used on Tower 007/061 on Caribou-Palermo South (bottom).

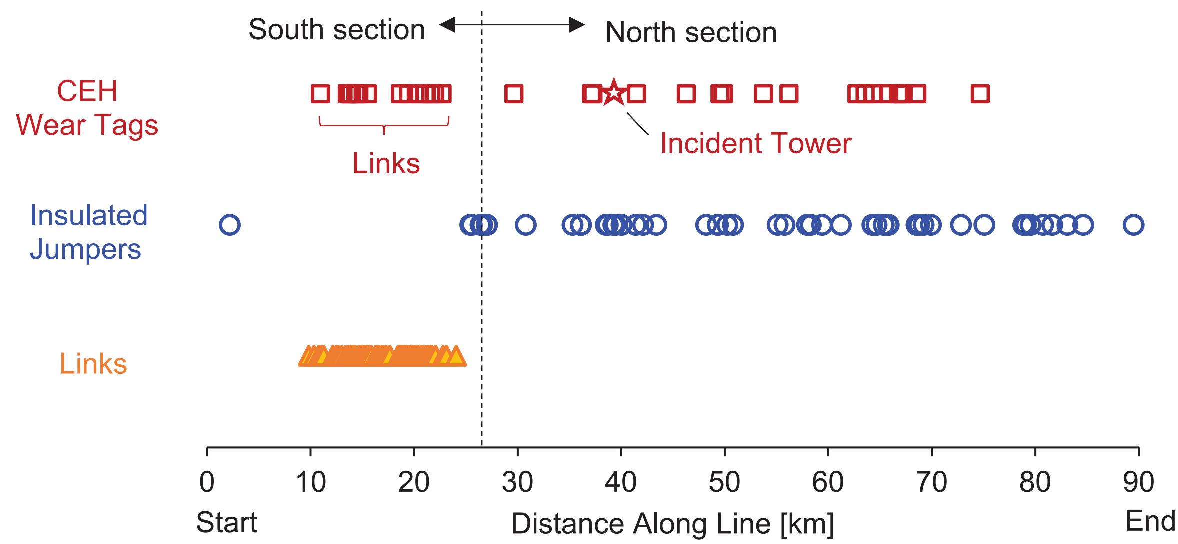


Figure 21. High-priority cold-end hardware / wear tags mapped in conjunction with link connectors and insulated jumpers on Caribou-Palermo.

Insulated Jumper Analysis

Dead-end insulators require a jumper to electrically connect the two ends of the conductor. In some instances, such as when conductors are transposed (when their positions are swapped to equalize mutual inductance and impedance), or the jumper is at risk of contacting the tower, an insulator is used to suspend the jumper away from the tower, preventing undesirable jumper-tower contact. In regions such as the North Fork Feather River Canyon, jumper insulators are more common and may be associated with the increase in cold-end hardware / wear tags, as discussed below and shown in Figure 21. Example photographs of worn cold-end hardware on jumper insulators are shown in Figure 22.

Caribou-Palermo North
SAP: 40747408
B Tag

CRO
SAP: 40911292
B Tag

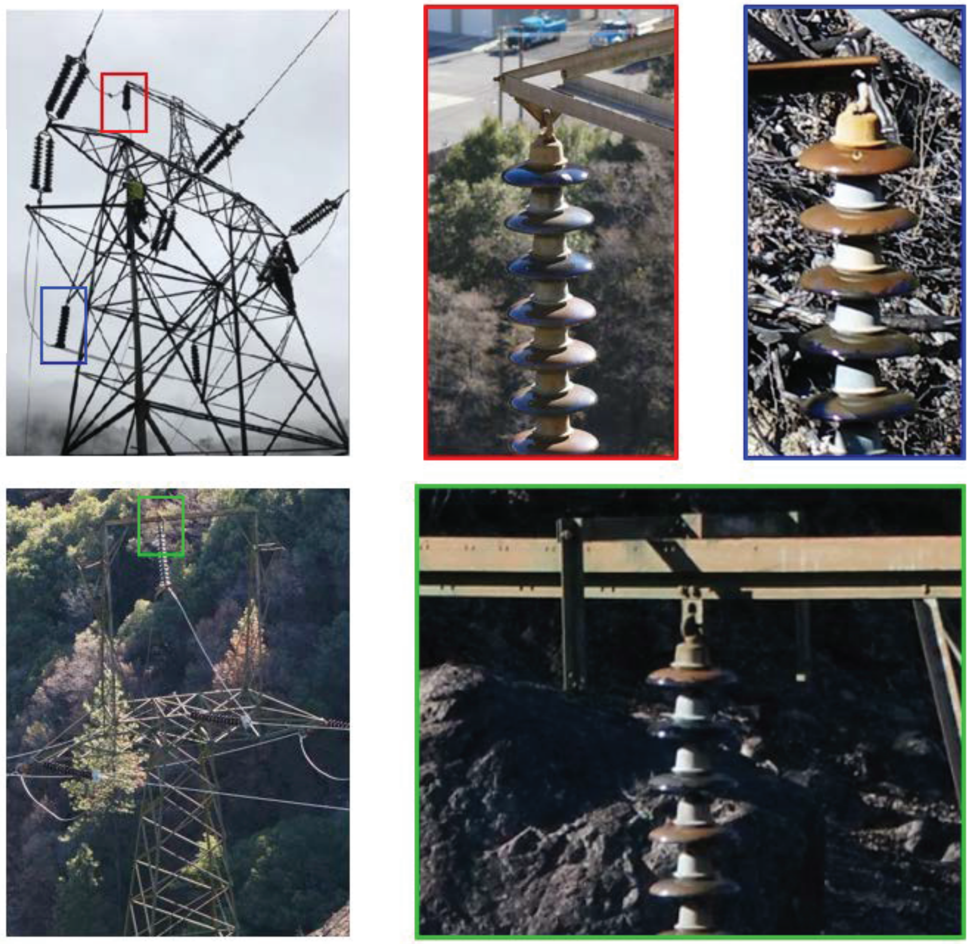


Figure 22. Representative jumper insulator cold-end hardware / wear tags within the North Fork Feather River Canyon.

Using the post–Camp Fire drone inspection data, the hot end (conductor end) of each insulator-to-tower attachment point was characterized as attaching to either the main line or a jumper. Insulators connected to jumpers on Caribou-Palermo were found primarily on Caribou-Palermo North, as shown in Figure 21. Roughly one-sixth of Caribou-Palermo North structures contained insulated jumpers. However, more than 60 percent of the high-priority cold-end hardware / wear tags on Caribou-Palermo North were associated with structures that contained insulated jumpers, as shown in Figure 23.

Suspended insulators attached to the jumpers are likely not subjected to Aeolian vibration conditions traditionally associated with tensioned conductors. Rather, insulated jumper connector wear is likely the result of greater freedom of movement between the conductor/insulator couple and the tower, specifically due to the low jumper line tension. A breakdown of Caribou-Palermo North structures with cold-end hardware / wear tags is given in Figure 24.

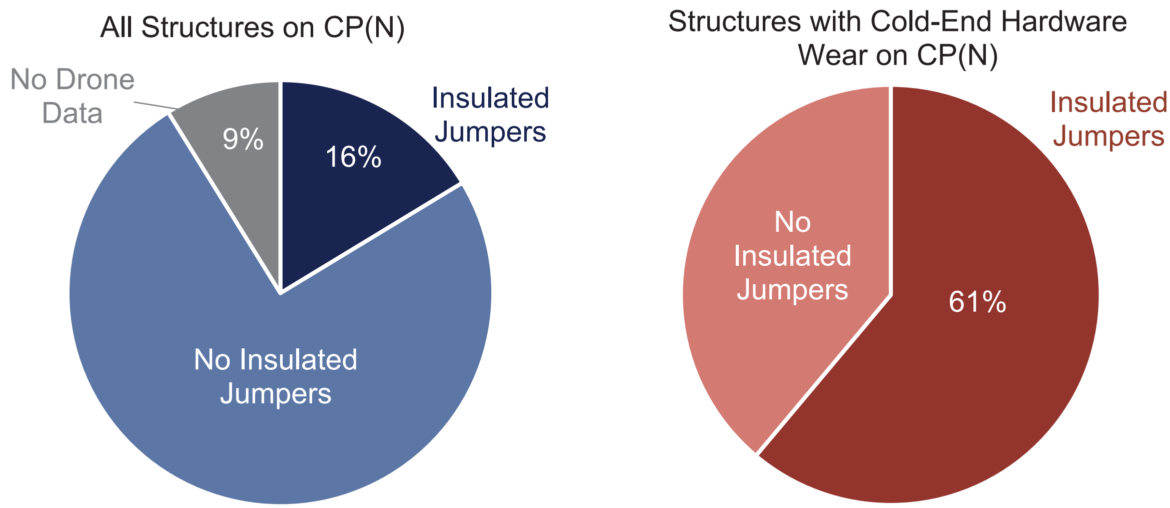


Figure 23. Pie charts showing the percentage of post–Camp Fire structures with insulated jumpers on Caribou-Palermo North (left), compared to the number of structures with insulated jumpers with cold-end hardware / wear tags (right).

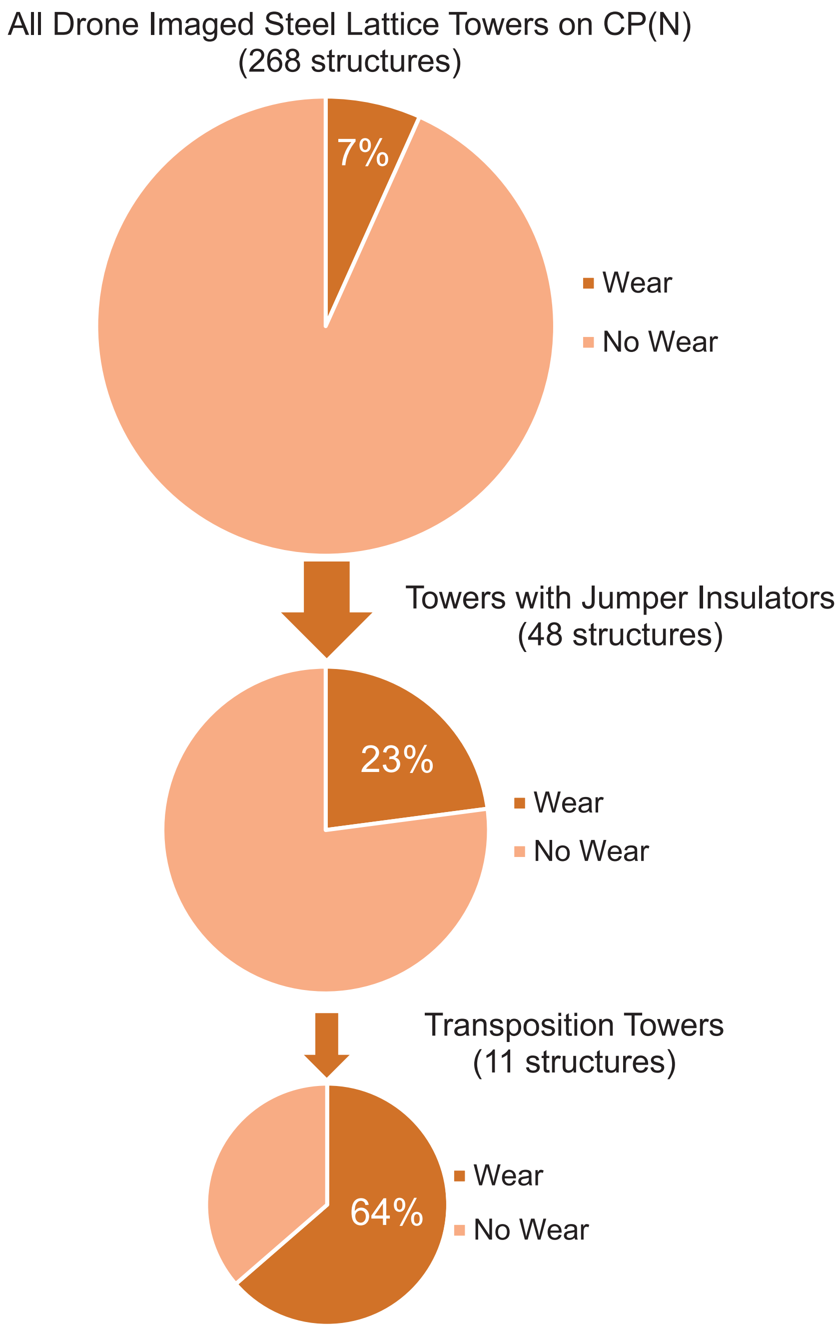


Figure 24. Breakdown of Caribou-Palermo North cold-end hardware / wear tag rates for all steel lattice towers, all steel lattice towers with jumper insulators, and all transposition towers. All transposition towers on Caribou-Palermo North contain jumpers attached to insulators.

Normalized counts of insulators attached to jumpers for the Caribou-Palermo, Cresta–Rio Oso (CRO), Drum-Higgins (DH), Drum–Rio Oso (DRO), Paradise–Table Mountain (PTM), and Bucks Creek–Rock Creek–Cresta (BCRC) lines are shown in Figure 25, as determined from post–Camp Fire drone inspection data. We note that normalized counts for PTM and BCRC were determined from a relatively small number of steel lattice towers, based on the available drone inspection photos at the time of analysis. CRO and BCRC, which exhibited high normalized counts of cold-end hardware / wear, comparable to Caribou-Palermo (Figure 15), also have high normalized counts of insulated jumpers. Of the 16 high-priority cold-end hardware / wear tags on BCRC and CRO, nine (56%) were associated with insulators attached to jumpers.

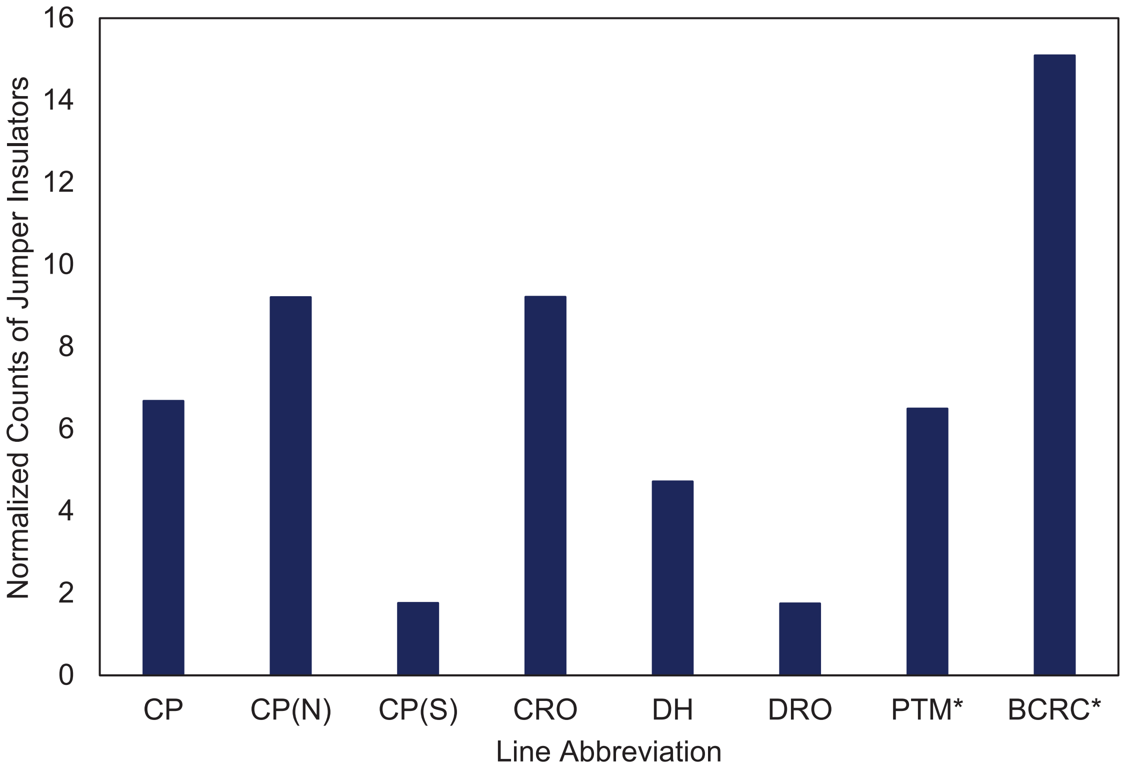


Figure 25. Normalized counts of insulated jumpers on Caribou-Palermo (CP) and selected comparison lines. Counts of insulators attached to jumpers were normalized by the total number of drone-inspected insulator-tower attachment points as of May 13, 2019, and multiplied by 100. (* Fewer than 21 drone-inspected steel lattice towers as of May 13, 2019.)

Transposition Towers

The Caribou-Palermo tower reportedly associated with the Camp Fire (Tower :027/222) was a transposition tower, and the incident C-hook was reportedly on an insulator attached to a jumper rather than the main line. Photos of Tower :027/222 are shown in Figure 26. Caribou-Palermo North transposition towers contained jumpers attached to suspended insulators. Eleven transposition towers were identified on Caribou-Palermo North, and seven of these (64 percent)

were given high-priority cold-end hardware / wear tags following the Camp Fire. Transposition towers and cold-end hardware / wear tags are mapped in Figure 27. These seven wear tags represent 39 percent of the cold-end hardware / wear tags on Caribou-Palermo North. Each of these Caribou-Palermo North transposition towers contains a steel bar that bridges two jumper insulators, shown in Figure 28. This specific assembly appears to be unique to Caribou-Palermo North and PTM, and its role in long-term cold-end hardware wear is unknown at this time. The southern portion of PTM contained two transposition towers with similar construction to the incident transposition tower :027/222. One of these two PTM towers had a "B" priority cold-end hardware related wear tag. Neighboring BCRC and CRO transposition towers have a similar bridging bar on transposition towers. However, the bar does not appear to pass through the shoe as in the Caribou-Palermo North transposition towers.

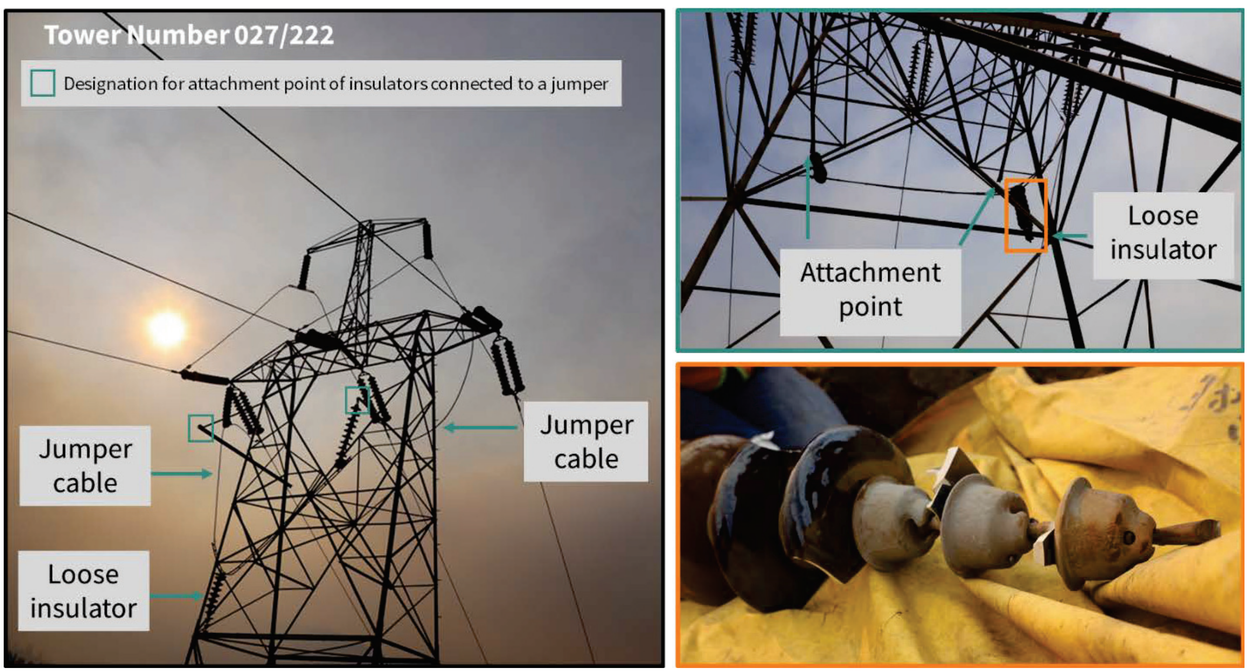


Figure 26. Images of the incident Tower :027/222 after the 2018 Camp Fire.

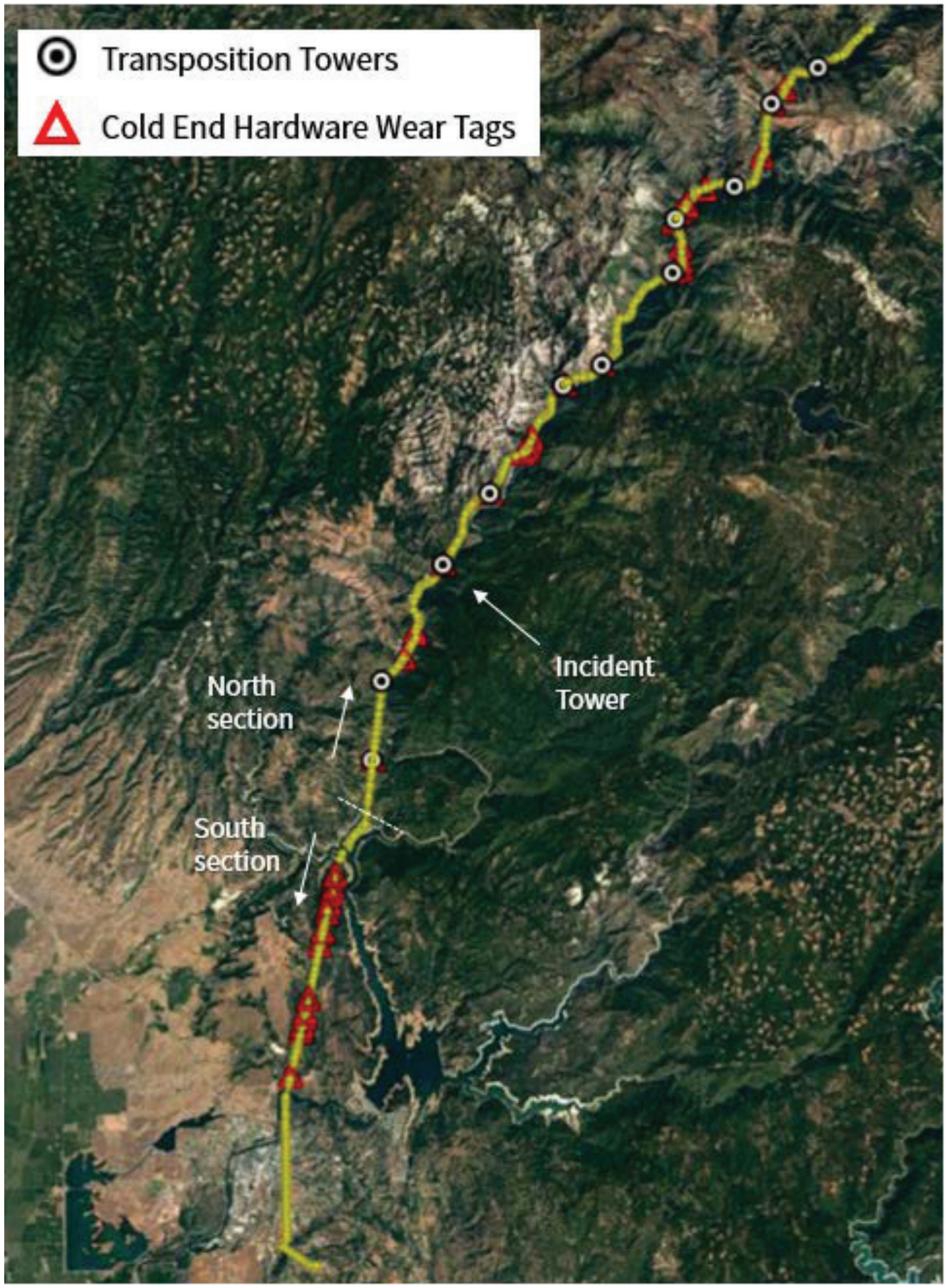


Figure 27. Map of Caribou-Palermo showing the north-south dividing line, cold-end hardware / wear tags, and transposition towers.

Figure 28. Photograph of transposition Tower :032/260 on Caribou-Palermo North showing the jumper suspended from insulators with an attached steel bar.

Cold-End Hardware / Wear Summary

There were 32 high-priority cold-end hardware / wear tags on Caribou-Palermo from November 8, 2018, to June 19, 2019. These tags were approximately split 60 percent / 40 percent between the northern and southern portions of Caribou-Palermo, shown in Figure 29. All of the 14 high-priority cold-end hardware / wear tags on Caribou-Palermo South were on structures with link connections. Of the 18 high-priority cold-end hardware / wear tags on Caribou-Palermo North, 11 (61 percent) were on dead-end towers with insulated jumpers, depicted in Figure 30. The remainder were on standard suspension towers. Seven of these 11 dead-end towers were transposition towers with the bar shown in Figure 28.

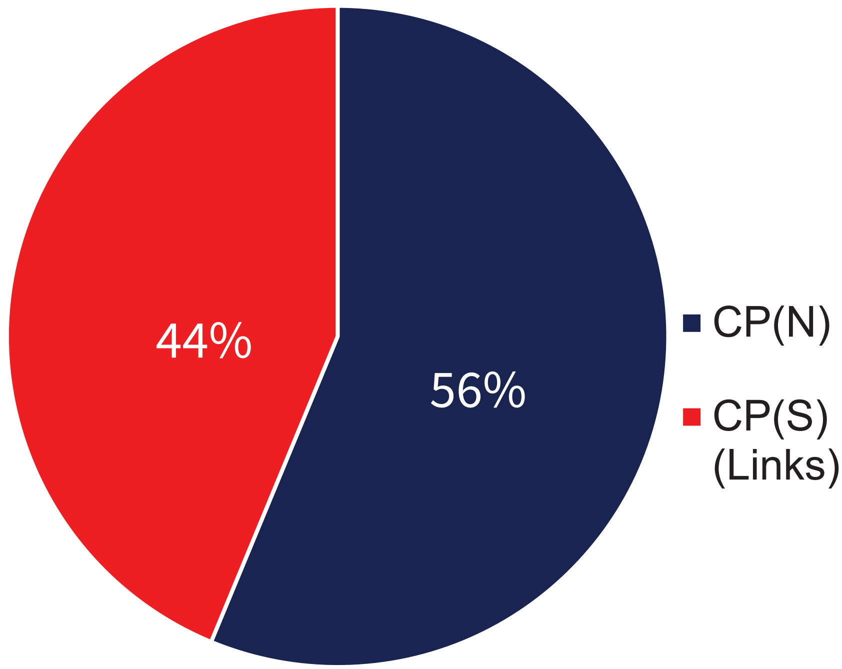


Figure 29. Breakdown of cold-end hardware / wears tags on the entire Caribou-Palermo line.

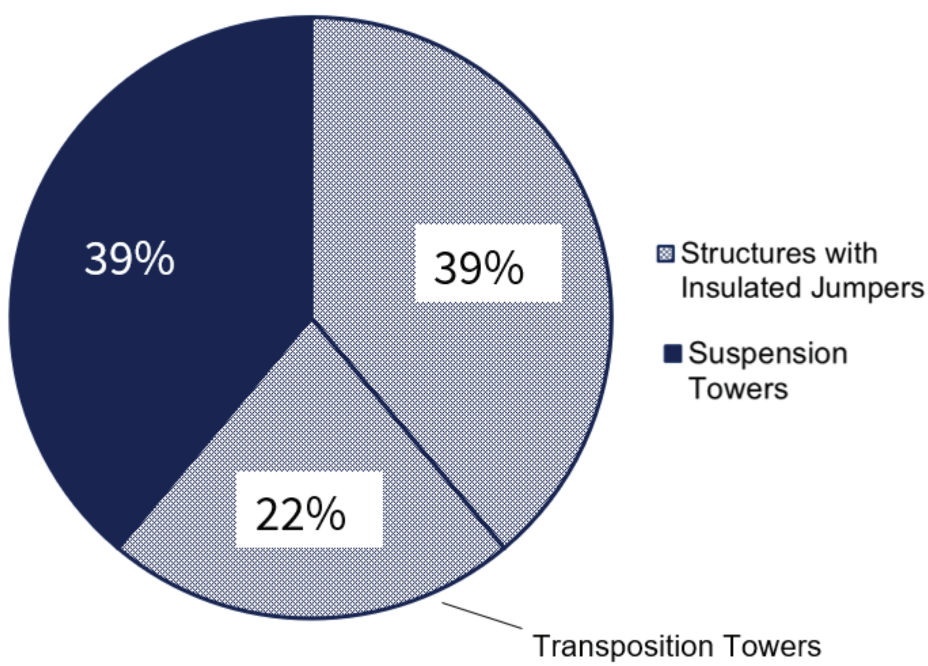


Figure 30. Breakdown of cold-end hardware / wear tags on Caribou-Palermo North.

Variation in Hanger Plate Specifications

Construction drawings were reviewed for structures located on parts of the Caribou-Palermo line as well as comparison lines. A wide variety of structure and component designs were found across both Caribou-Palermo and comparison lines. Of note is the variety of hanger plate designs utilized. According to the design books, certain towers on comparison lines, such as Drum–Rio Oso (DRO), have 5/8-inch-thick hanger plates. Towers where 5/8-inch-thick hanger plates were found include double-circuit suspension and dead-end towers on DRO circa 1930, as well as single-circuit snow towers on DRO circa 1919 (Figure 31 and Figure 32). In contrast, some towers originally installed on the original Caribou–Golden Gate line (portions of which make up modern-day Caribou-Palermo) contain 3/8-inch-thick hanger plates (Figure 33). While the towers depicted in Figure 31 through Figure 33 do not appear on the modern-day Caribou-Palermo line, they provide examples of hanger plate thickness variation in similar voltage transmission towers of similar vintage. The Caribou-Palermo North line (or others within the North Fork Feather River Canyon) hanger plate thicknesses are currently unknown. Thinner hanger plates may experience more wear under given environmental conditions due to decreased contact area with attached connectors.

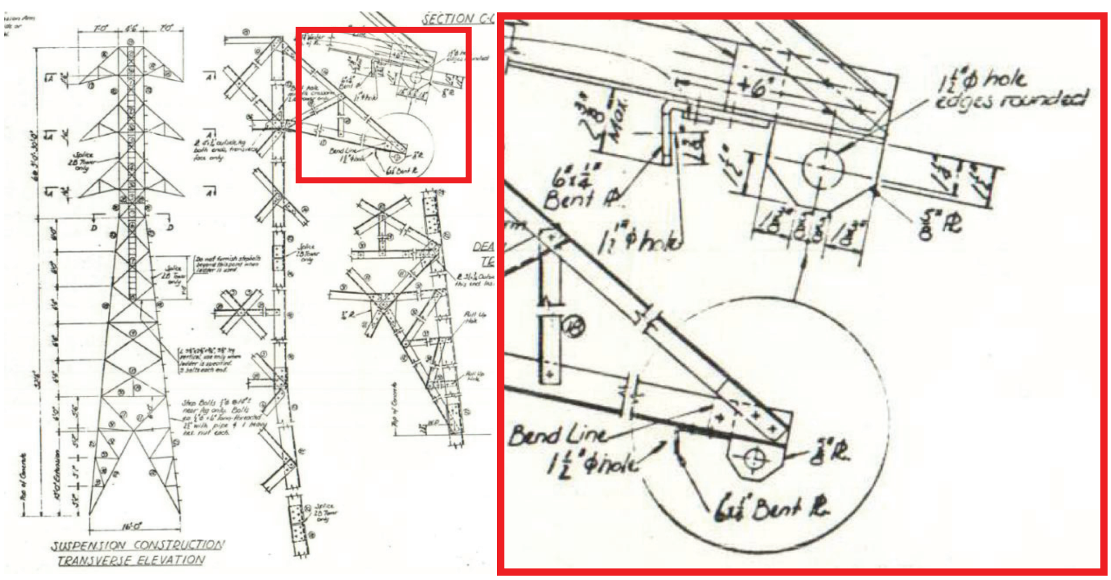
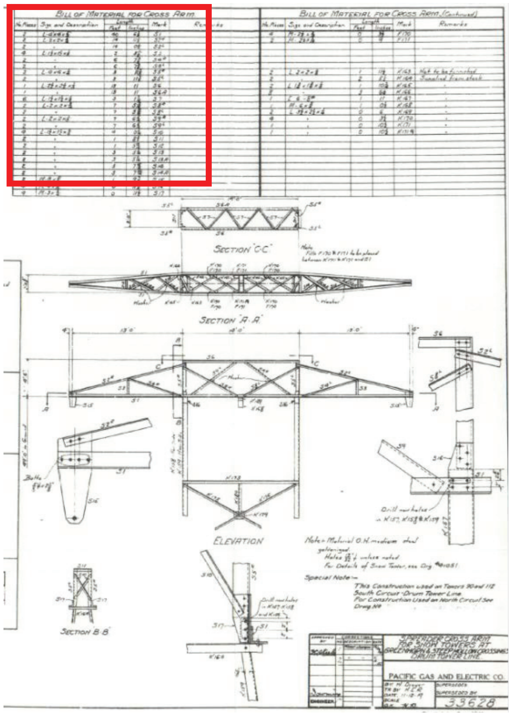
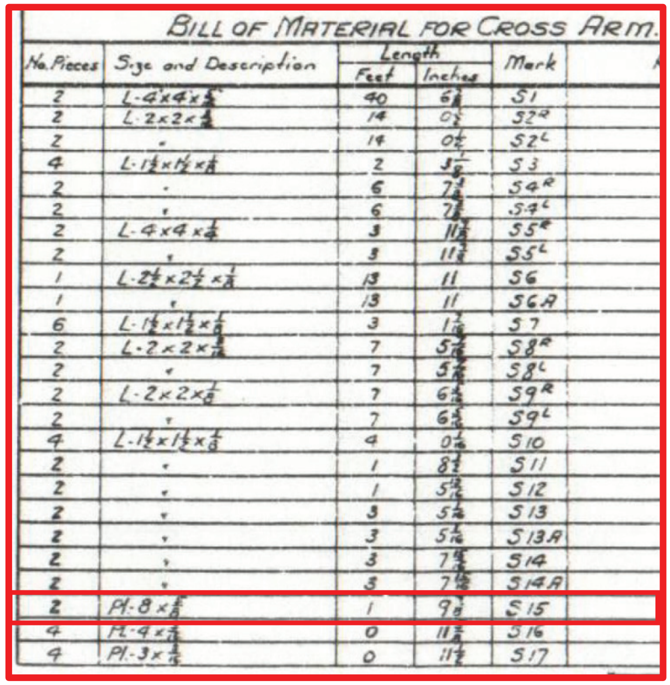


Figure 31. Drawing of “Suspension Construction Transverse Elevation” Types 2A and 2B towers from Drum–Rio Oso 115 kV design book dated October 20, 1930. The hanger plates used in these towers are 5/8 inch thick and have a 1 ½-inch-diameter eye.





BILL OF MATERIAL FOR CROSS ARM.

No. Pieces	Size and Description	Length Feet	Length Inches	Mark
2	L-4x4x5/16	40	6 1/8	S1
2	L-2x2x3/16	14	0 1/2	S2R
2	"	14	0 1/2	S2L
4	L-1½x1½x3/16	2	3 1/8	S3
2	"	6	7 3/8	S4R
2	"	6	7 3/8	S4L
2	L-4x4x1/4	3	11 3/8	S5R
2	"	3	11 3/8	S5L
1	L-2½x2½x3/16	13	11	S6
1	"	13	11	S6A
6	L-1½x1½x3/16	3	1 7/16	S7
2	L-2x2x3/16	7	5 7/16	S8R
2	"	7	5 7/16	S8L
2	L-2x2x1/8	7	6 5/16	S9R
2	"	7	6 5/16	S9L
4	L-1½x1½x1/8	4	0 1/16	S10
2	"	1	8 1/2	S11
2	"	1	5 13/16	S12
2	"	3	5 1/16	S13
2	"	3	5 1/16	S13A
2	"	3	7 15/16	S14
2	"	3	7 15/16	S14A
2	Pl-8x5/8	1	9 3/8	S15
4	Pl-4x3/16	0	11 3/8	S16
4	Pl-3x3/16	0	11 1/2	S17

Figure 32. Drawing of a "Spreader Cross Arm" for snow towers at Greenhorn and Steephollow crossing from Drum–Rio Oso 115 kV design book dated November 12, 1919. The hanger plates used in these towers are 5/8 inch thick and have a 1 ½-inch-diameter eye.

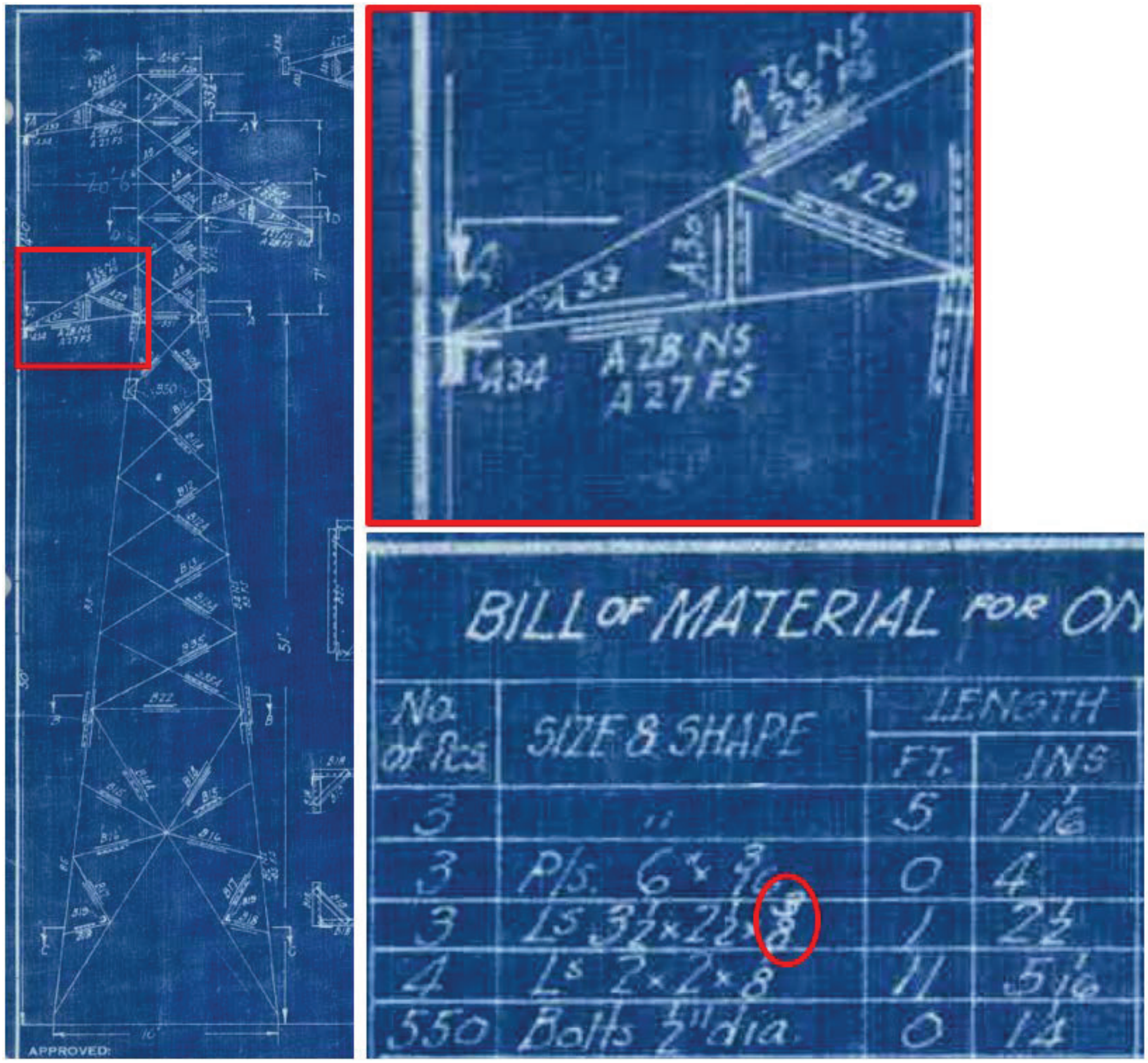


Figure 33. Drawing of “Valley Suspension “B” Tower” dated June 14, 1920. This is a valley dead-end tower originally installed on the 165 kV Caribou–Golden Gate Line. The hanger plates used in these towers are 3/8 inch thick.

Conductor Type

Six distinct conductor types or sizes are present on Caribou-Palermo, shown on the map in Figure 34. Most of the line (36.8 mil) is composed of 452.3 kcmil aluminum conductor steel-reinforced (ACSR), which consists of aluminum strands wrapped around a steel core. A large section of the southern end of Caribou-Palermo (13.2 mi) is composed of 167.8 kcmil copper (Cu). Two short sections of the line (2.2 mi and 1.5 mi) are composed of 397.5 kcmil or 715.5 kcmil all-aluminum conductor (AAC), which consists of aluminum strands wrapped around an aluminum core. Finally, two short line sections (0.9 mi and 0.6 mi) are composed of

397.5 kcmil ACSR or 795 kcmil ACSR. Conductor sizes and types used in Caribou-Palermo and comparison line jumpers are unknown and were not analyzed.

To determine whether conductor type correlates with wear tags, the locations of Caribou-Palermo cold-end hardware / wear tags were overlaid on a map of Caribou-Palermo conductor types, shown in Figure 35. A high concentration of cold-end hardware / wear tags was found on Caribou-Palermo South, where a copper conductor is used. These tags were associated with link connections, as described in a previous section. Cold-end hardware / wear tags were also found throughout the length of Caribou-Palermo, including in segments composed of 452.3 kcmil ACSR, 795 kcmil ACSR, and 397.5 kcmil AAC.

Conductor type and size may influence the susceptibility of a line to motion that could affect cold-end hardware. For example, conductors with greater diameter (greater cross-sectional area) and/or reduced weight are more susceptible to vibration and galloping. Therefore, differences in conductor type could result in one line experiencing conductor motion under a given set of environmental conditions (wind, precipitation, temperature, etc.), while a parallel line in the same location and environmental conditions may not. Diameters and weights for each Caribou-Palermo conductor type are shown in Table 3.

Susceptibility to wind-induced conductor motion increases with conductor diameter and decreases with conductor weight. Of the conductor types and sizes on Caribou-Palermo, 167.8 kcmil Cu has the lowest susceptibility to wind-induced conductor motion due to its low diameter/weight ratio, whereas 397.5 kcmil ACSR and 715.5 kcmil AAC have increased susceptibility. The high concentration of cold-end hardware / wear tags on the copper section of Caribou-Palermo, which has the lowest susceptibility to wind-induced conductor motion, indicates that conductor type is likely not a dominant factor in the location of high-priority tags on Caribou-Palermo. Rather, the cold-end connection link design (as described above) appears to be a primary factor associated with Caribou-Palermo South wear tags.

Conductor types were also examined for three lines running parallel to Caribou-Palermo in or near the North Fork Feather River Canyon, BCRC, CRO, and PTM, as shown in Figure 34. BCRC and CRO are composed of 795 kcmil ACSR and run parallel to segments in the middle of Caribou-Palermo that are composed primarily of 452.3 kcmil ACSR. The larger diameter/weight ratio for Caribou-Palermo would suggest a greater susceptibility to wind-induced conductor motion in this section of Caribou-Palermo. However, BCRC and CRO also exhibited increased normalized counts of cold-end hardware / wear tags compared to other comparison lines, Figure 15. The section of PTM that runs parallel to Caribou-Palermo is composed of a conductor type that is more susceptible to wind-induced conductor motion. However, this section of PTM exhibited fewer cold-end hardware / wear tags than Caribou-Palermo. These comparisons lend further evidence that differences in conductor type, while a factor in conductor motion, are likely not a primary cause of the increased post–Camp Fire high-priority tags associated with the Caribou-Palermo line.

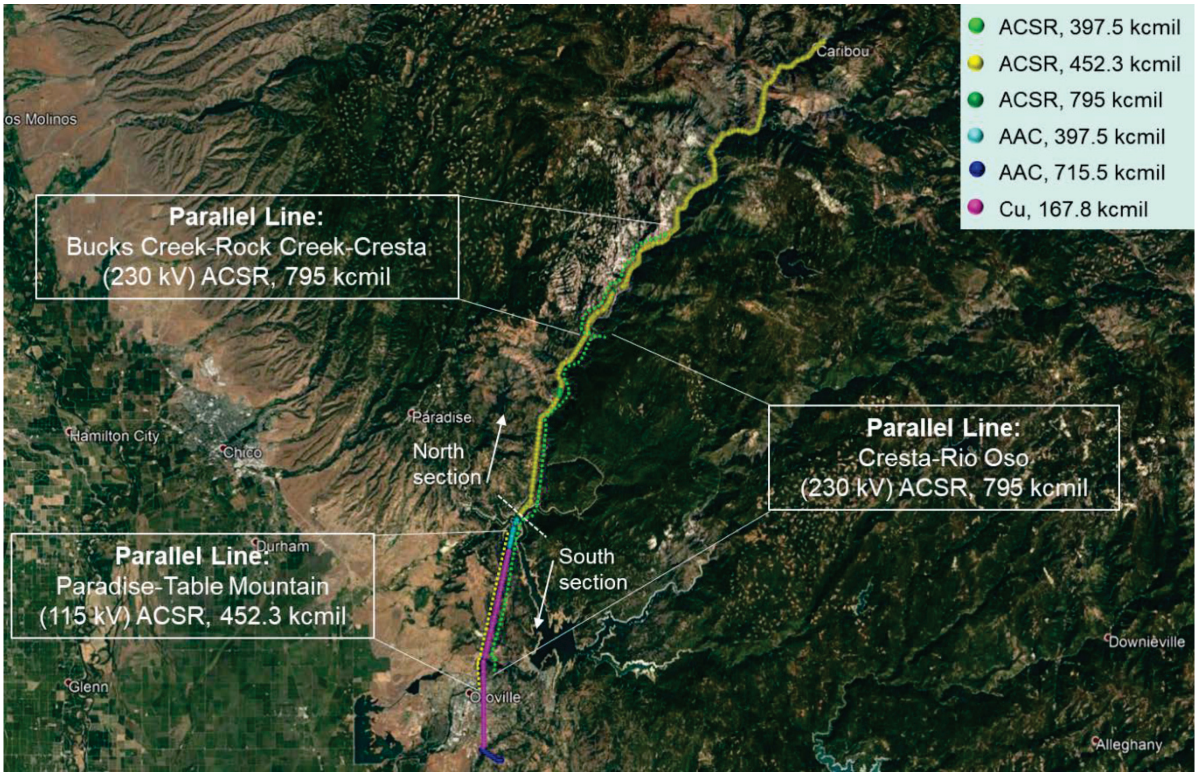


Figure 34. Map of conductor types used in Caribou-Palermo and in parallel lines running adjacent to Caribou-Palermo.

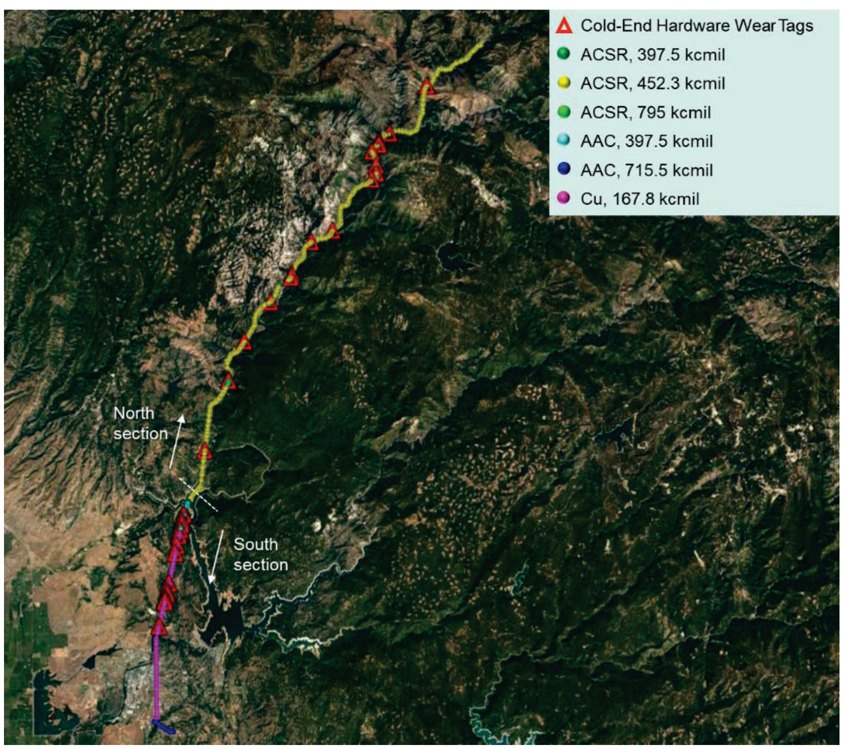


Figure 35. Map of Caribou-Palermo cold-end hardware / wear tags and conductor types.

Table 3. Diameters and weights of conductor types on Caribou-Palermo.

Conductor Type	Conductor Size (kcmil)	Diameter (in.)	Weight (lbs./ft.)	Diameter/Weight Ratio (in./[lbs./ft.])
ACSR	397.5	0.783	0.547	1.43
ACSR	452.3	0.830*	0.622*	1.33
ACSR	795.0	1.093	1.024	1.07
AAC	397.5	0.724	0.373	1.94
AAC	715.5	0.973	0.671	1.45
Cu	167.8	0.464	0.518	0.90

* Determined by linear interpolation.

Environmental Conditions

Wind Background

Although wind is broadly understood as a significant factor in the creation of extrinsic stresses in electrical transmission lines, the specific nature of those stresses may be dependent on a number of factors. In the present study, we have evaluated the influence of several environmental variables (temperature, precipitation, elevation, span length, span weight, maximum vs. average wind speeds, and wind direction relative to line orientation) on the location and frequency of the Caribou-Palermo and comparison line high-priority tags. Across the Caribou-Palermo line and each of the comparison lines, we identify damage modes that may be wind related, particularly cold-end hardware / wear tags. These damage tags are then compared against the various environmental factors to test for correlation.

Maximum and Average Wind Speed

Maximum (or peak) wind speeds in the areas of the chosen lines are generally found to vary between 60 to 100 mph, as measured and reported in "Extreme Wind Speed Estimates Along PG&E Transmission Line Corridors" across one-minute time intervals and at an elevation of 33 feet above ground level, over a 50-year return period. Peak wind speeds do not appear to show correlation with cold-end hardware / wear tag locations, as relatively few tags are present in regions associated with the highest wind speeds, as shown in Figure 36 and Figure 37. Though localized wind speeds may vary due to terrain features near structures, there is no obvious correlation between high peak speeds and damage. Furthermore, there is no observed correlation between high peak speeds and lines with higher damage rates. Of all comparison

lines considered in this report, Caribou-Palermo North shows the highest average wind speed at 10.7 mph, more than 45% greater than the average taken across all comparison lines, Figure 38.

High Wind Conditions

For the purposes of this study, to consider the possibility of direction-independent wind damage, a "high speed" wind conditions category was considered. This condition was defined as the length of time the line is subjected to wind greater than 10 m/s (22 mph). The 10 m/s "high" wind condition criterion was chosen as representative for relatively high sustained winds. These higher sustained winds are more likely to cause motion in non-tensioned lines and hardware, such as jumpers.

To help determine the extent to which each tower of each line is typically subjected to 10 m/s wind conditions, data were sourced from the NREL Wind Resource database. This database combines measured wind data with topographic/meteorological indicators to report wind speed and direction across the United States in one-hour increments. The year 2010 was selected for the generation of a dataset that shows the hour-by-hour behavior of each tower throughout an entire year, as well as the yearly average. Figure 39 displays a map of the wind in the area surrounding Caribou-Palermo and the comparison lines. As shown, northern portions of the Caribou-Palermo line experience among the highest yearly average wind speeds.

High wind conditions represent a relatively simple metric for measuring the wind incident on a given line, and again show that Caribou-Palermo North experiences elevated incident winds on average, more than three times the average taken across all towers on all comparison lines.

We then examined each individual tower to determine whether it spends an elevated amount of time under high wind conditions. About 10 percent of towers experience 605 hours or more of wind greater than 22 mph per year, so this was set as the cutoff (Figure 40). If wind were a major contributing factor, it would follow that a large number of high-wind towers would correlate to an increased damage tag rate. Fifteen of the 28 lines examined show nearly no high-wind towers (4 percent or less), and only four exceeded 21 percent: Caribou-Palermo North, Humboldt-Bridgeville (HB), Pit #4 Tap (P4T), and Rock Creek–Poe (RCP), Figure 41. Nearly half of the towers in Caribou-Palermo North are high-wind towers, the highest rate of any line examined. A map of high-wind towers overlaid with high-priority cold-end hardware / wear tags is shown in Figure 42. Many of the Caribou-Palermo North towers that exhibit high-priority cold-end hardware / wear tags are exposed to elevated wind conditions.

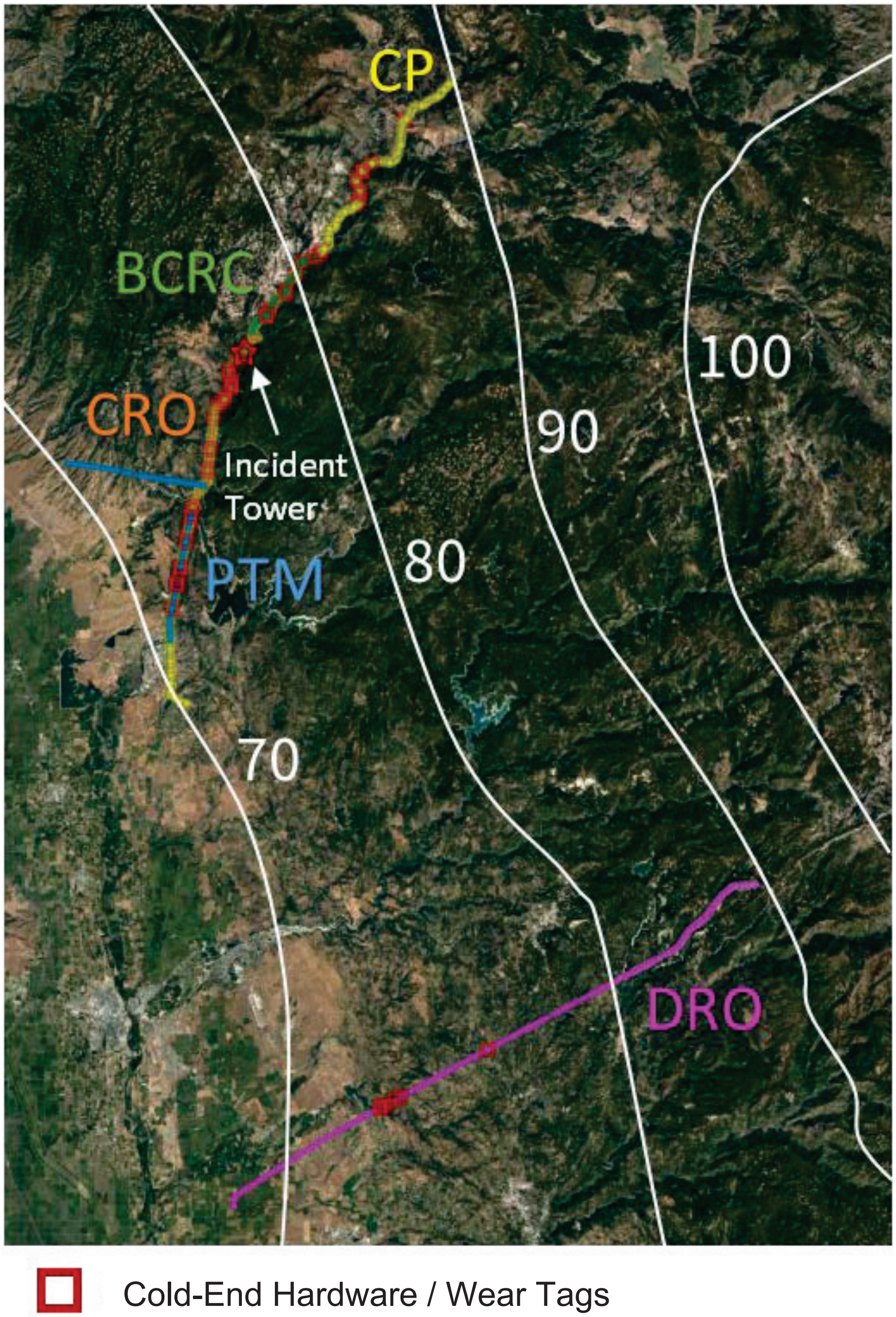


Figure 36. Contour map of peak wind speed (50-year return period) in the area of Caribou-Palermo and the comparison lines, with "A" and "B" cold-end hardware / wear tags highlighted. No obvious correlation between peak wind speed and damage locations is observed. Speeds are reported as the maximum one-minute interval at 33 feet above ground level.

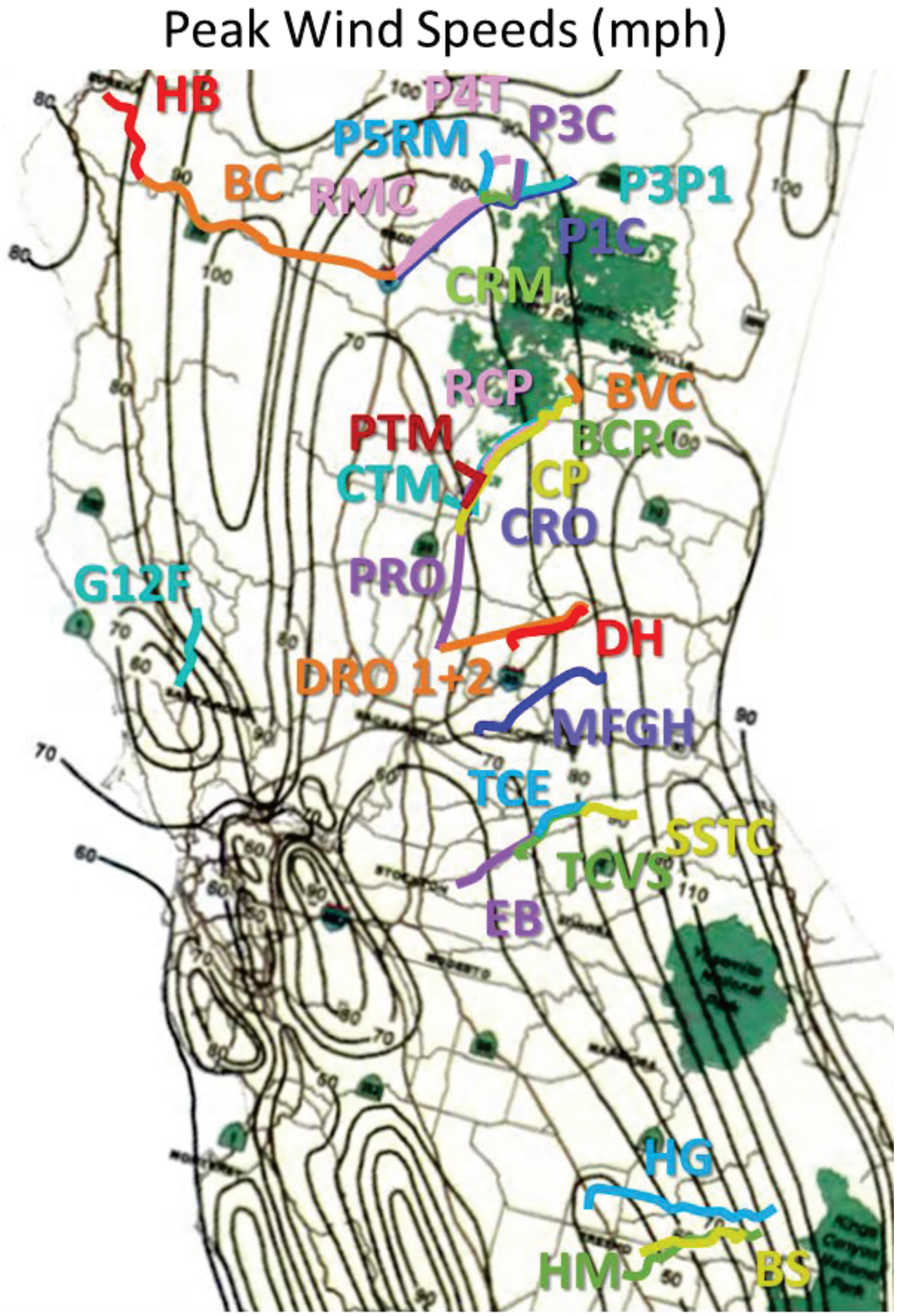


Figure 37. Contour map of peak wind speeds across Caribou-Palermo and comparison lines. No obvious correlation between peak wind speeds and lines with higher tag rates is observed. Speeds are reported as the maximum one-minute interval at 33 feet above ground level, over a 50-year return period.

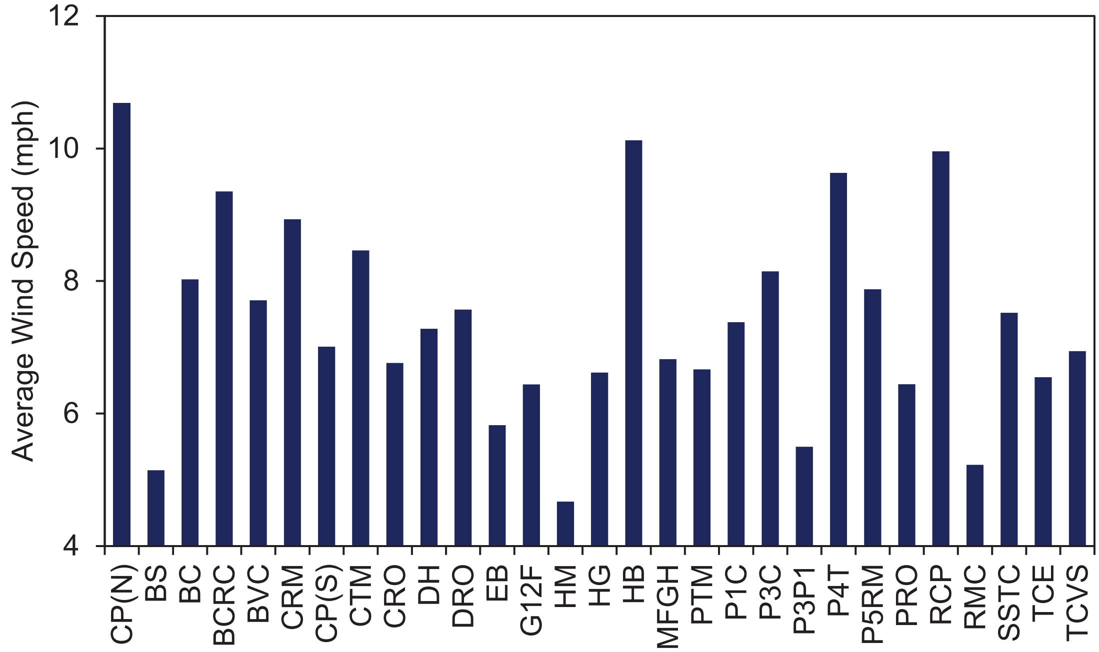


Figure 38. Average wind speed measured across all towers in the given line. All data obtained from the year 2010 in the NREL Wind Database.

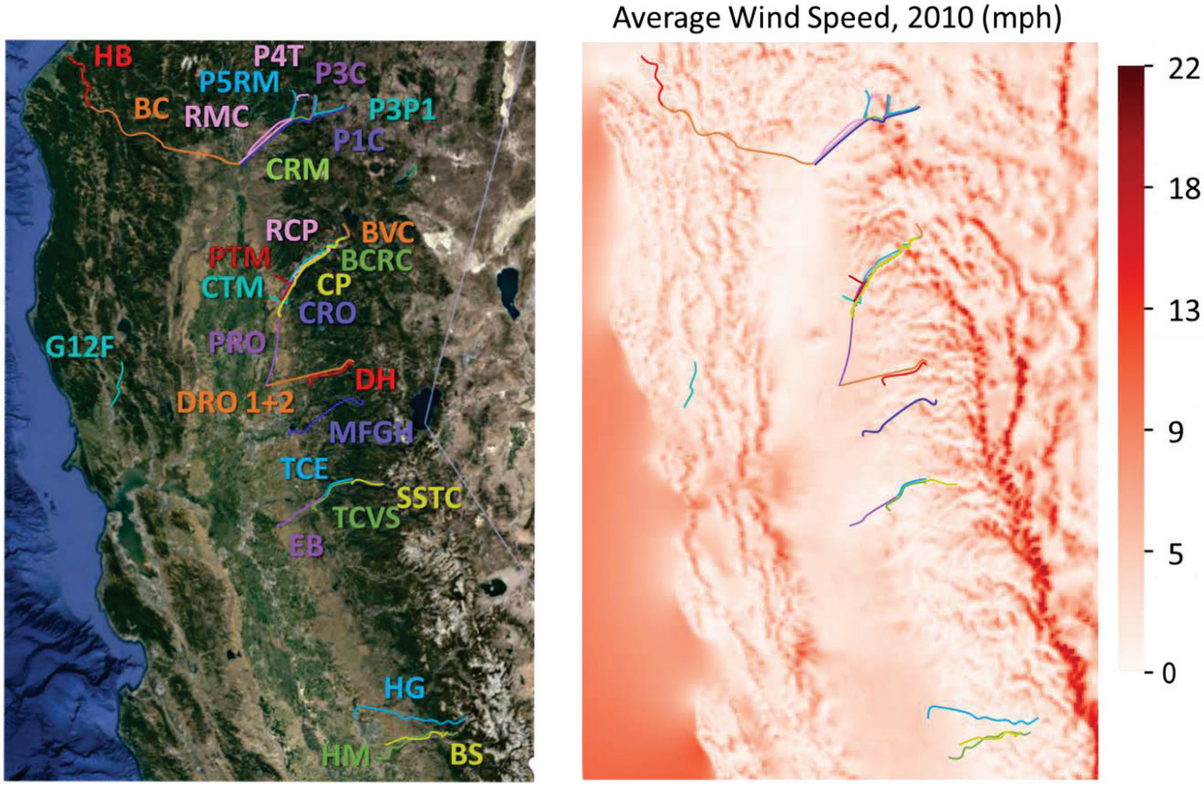


Figure 39. Average wind speed in 2010 in the areas surrounding Caribou-Palermo and comparison lines.

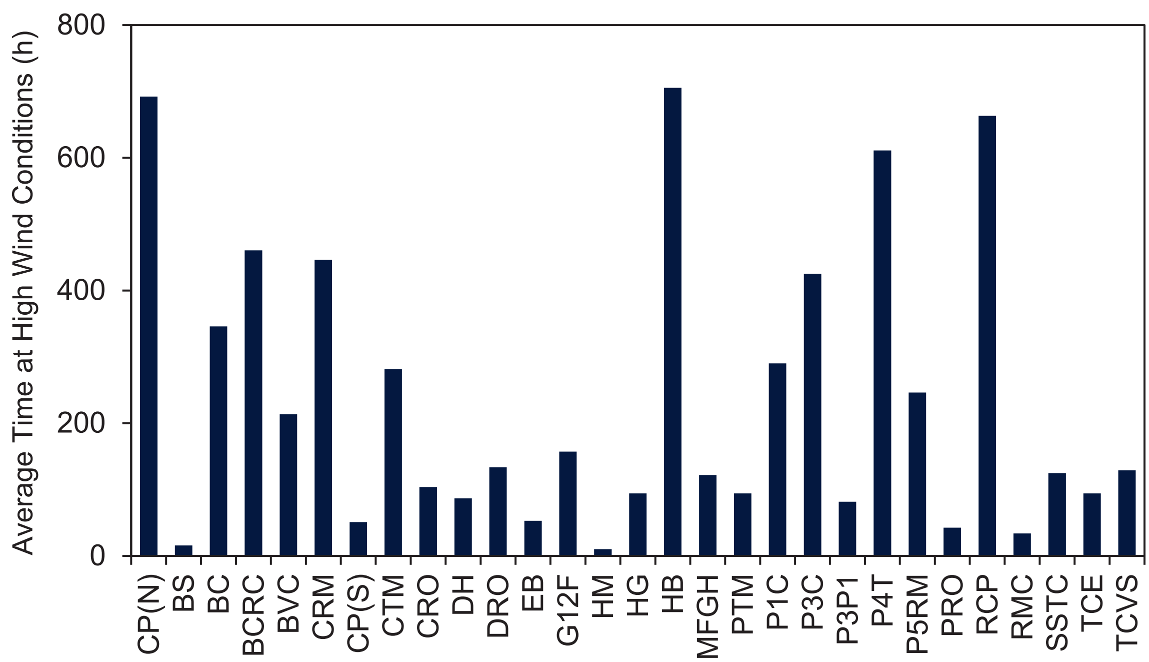


Figure 40. Average hours per year at high wind conditions (>22mph), measured across all towers.

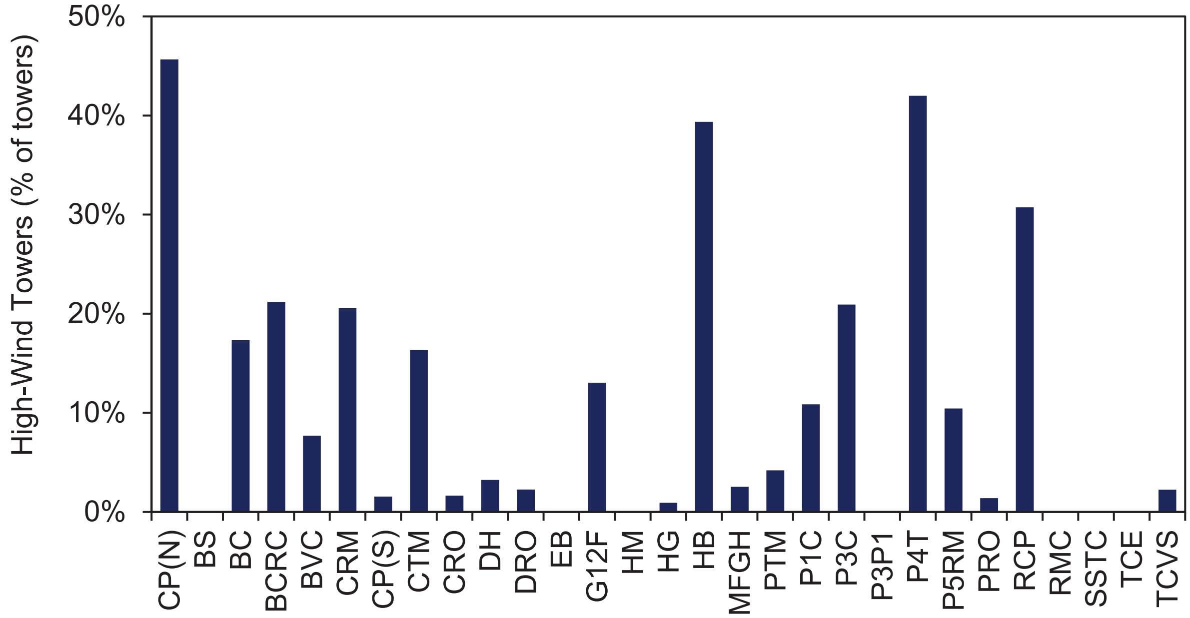


Figure 41. Number of towers that experience >605 hours of high wind conditions (>22mph) per year, measured as a percentage of total towers in the given line.

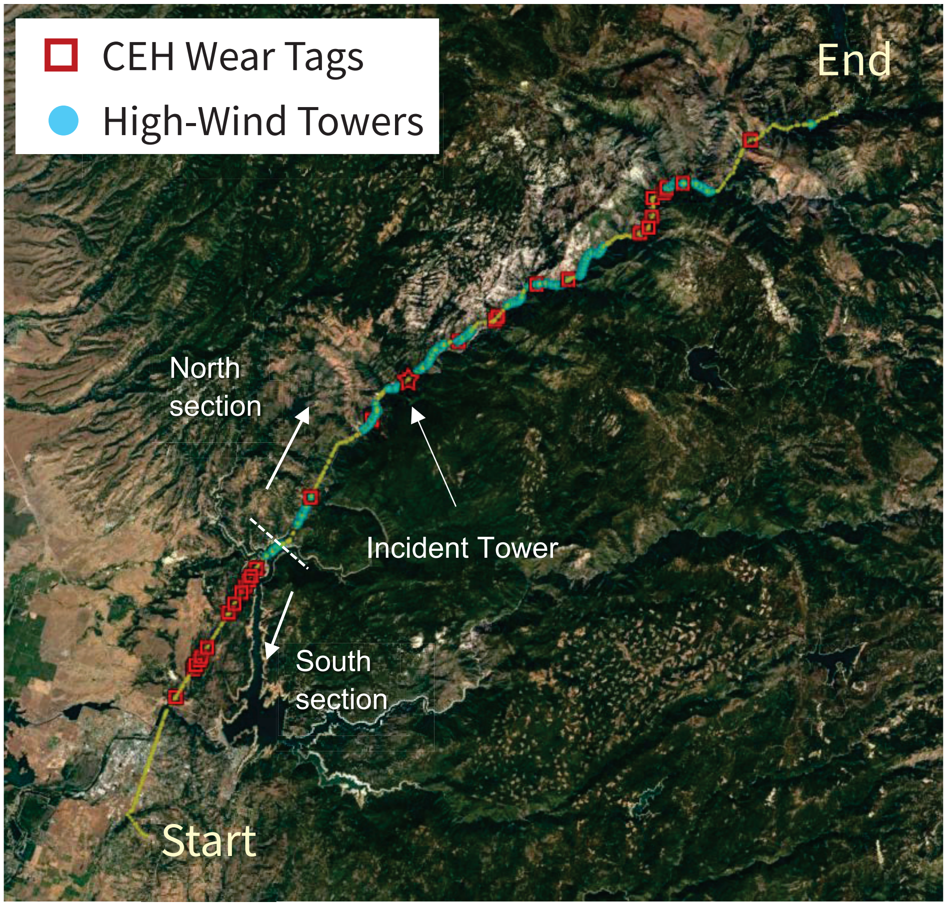


Figure 42. Map of all towers in the Caribou-Palermo line, with high-wind towers and cold-end hardware (CEH) wear tags overlaid.

Cyclic Conductor Motion and Wind

Even on days where wind speeds are low (as little as 2 mph), the forces exerted by wind may be sufficient to excite cyclic conductor motion, a key factor in the creation of progressive damage via fatigue or wearing of tower components and hardware. Two primary categories of this cyclic motion are considered: Aeolian vibrations and conductor gallop. Aeolian vibration occurs when a line experiences relatively low wind speeds (2–15 mph) traveling transverse to the heading of the line. This creates trailing vortices that excite a high-frequency (3–150 Hz), low-amplitude (0.01-1x conductor diameter) oscillation. At higher transverse wind speeds (15+ mph), and under the correct environmental conditions to produce icing on the line, conductors may "gallop." (Under particular conditions, "bare gallop" can occur in the absence of icing, but these incidents are rare.)[4] In this mode, the asymmetric cross section caused by icing allows the wind to generate lift and produces a low-frequency (0.08–3 Hz), high-amplitude (5-300x conductor diameter) oscillation. Aeolian vibrations are known to produce long-term wear in overhead

[4] Transmission Line Reference Book: Wind Induced Conductor Motion, EPRI, 1979.

lines, whereas gallop is more often associated with discrete damage events, though the two mechanisms can work in concert to exacerbate damage created during previous events.[5]

In addition to wind speed and direction, other climate conditions sourced from the NREL database include temperature and precipitation, as shown in Figure 43 and Figure 44. Each of the chosen lines tends to travel through multiple climate conditions, with lower average temperatures and higher average precipitation generally corresponding to higher elevations. The northern portions of Caribou-Palermo are subjected to relatively low average temperatures that could increase the risk of ice formation and cyclic conductor motion via galloping. Given the highly seasonal nature of these data, these conditions should be considered as broad summaries of conditions, with subsequent analyses making use of hour-by-hour temperature and precipitation data.

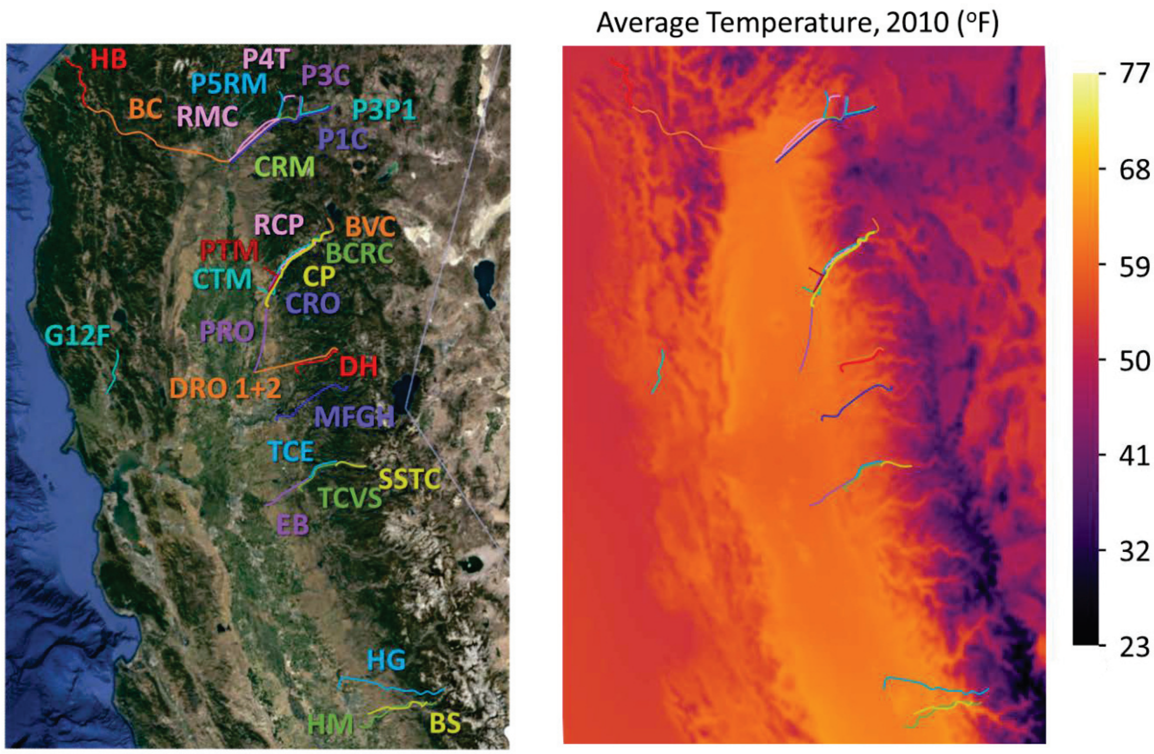


Figure 43. Average temperature in 2010 in the areas surrounding Caribou-Palermo and the selected comparison lines.

5 Transmission Line Reference Book: Wind Induced Conductor Motion, EPRI, 1979.

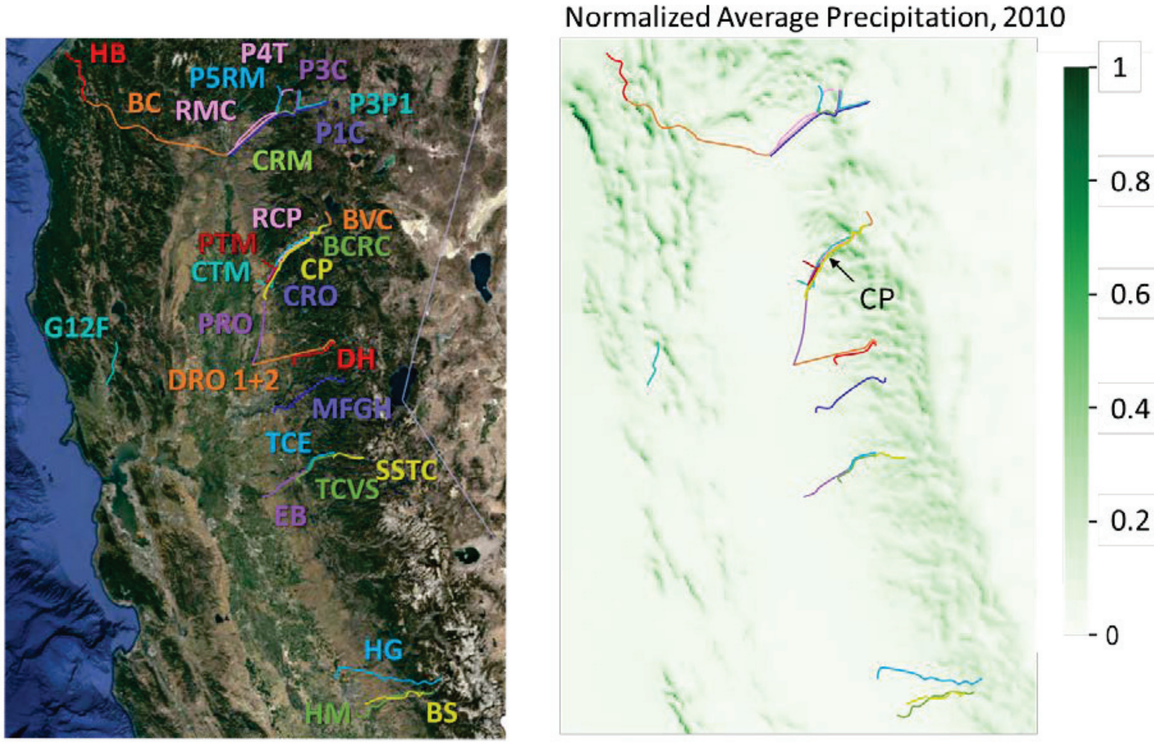


Figure 44. Normalized average precipitation in 2010 in the areas surrounding Caribou-Palermo and the selected comparison lines.

Several metrics were developed to help assess possible contributors to sustained cyclic conductor motion over time. Yearly time at Aeolian conditions was defined as the number of hours per year where the transverse-to-span wind speed vector is between 2 and 15 mph. The average number of hours in these conditions per year is relatively high, so these are compared in terms of hours above or below the average time of 5,765 hours. Time at galloping conditions was defined as any hour in which incident wind speed is above 15 mph and the temperature is at or below 3°C, which has generally been found in past studies as the temperature at which a sufficient amount of ice may be present to produce galloping effects.[6] High wind conditions are defined as any hour in which wind speed is above 22 mph (independent of direction), and these data are further analyzed by calculating the percentage of the towers for a given line that spend greater than 605 hours in high wind conditions per year.

Additional risk factors (several of which are considered elsewhere in this report) include the age of the lines, the flexibility and configuration of hardware connections, the relative amount of friction at hardware connection points, conductor tension, and interactions between the natural structure/line frequency and the forcing frequency of the wind.

6 Transmission Line Reference Book: Wind Induced Conductor Motion, EPRI, 1979.

Temperature and Precipitation

No obvious correlation between temperature or precipitation and damage tags was observed. However, Caribou-Palermo notably has the lowest average temperature of all lines considered here, meaning that it may be more prone to icing and conductor galloping.

Aeolian Conditions

As described previously, Aeolian conditions are created by relatively low, sustained wind speeds traveling transverse to the line and are known to cause fatigue or wear damage over time in towers. Analysis of Aeolian conditions for a subset of comparison lines can be found in Table 4. This subset of lines was selected for additional analysis based on rates of damage tags and similarity to Caribou-Palermo. Caribou-Palermo shows significantly elevated time spent at Aeolian conditions compared to the other lines. Most significantly, the towers with cold-end hardware wear tags spend about 435 hours more time per year at Aeolian conditions when compared to the average.

Galloping Conditions

As described previously, galloping conditions are created by relatively high wind speeds traveling transverse to the line, when temperatures and environmental conditions are correct for the formation of ice on the line. Galloping events are typically associated with more acute damage such as larger-scale bending of tower structures but may also work in concert with other long-term damage modes to cause failures. Analysis of galloping conditions for a subset of comparison lines is shown in Table 4. Of the lines examined, Caribou-Palermo is one of the few lines that spends significant time at galloping conditions each year, more than double the next closest lines, BCRC and P4T, as portions of Caribou-Palermo extend further north and to higher elevations than the comparison lines. The towers with post–Camp Fire cold-end hardware wear tags and “A” damage tags (across all lines) also tend to spend an above-average amount of time at galloping conditions each year.

Table 4. Summary of wind factors for Caribou-Palermo and a selected set of comparison lines. Each is presented as an average of all structures in the given category.

	% of Towers, >605 Hours of High Wind per Year	High Wind Conditions (hours)	Aeolian Conditions (hours above avg.)	Gallop Conditions (hours)
Caribou-Palermo North	**46%**	**692**	**253**	**323**
Bucks Creek-Rock Creek-Cresta	21%	460	141	159
Caribou-Palermo South	2%	51	**202**	1
Cresta-Rio Oso	2%	104	54	6
Drum-Higgins	3%	87	6	14
Drum-Rio Oso	2%	134	-115	36
Paradise-Table Mtn	4%	94	-593	1
Pit #1-Cottonwood	11%	290	-599	131
Pit #4 Tap	42%	611	-126	145
All Tower Average	10%	222	0**	106
All Tower Stdev		408	836	243

** The average tower experiences 5,765 hours at Aeolian conditions per year.

For each line, a series of factors including elevation, span weight, temperature, precipitation, wind speed, time at Aeolian conditions, time at galloping conditions, and tower connection types were mapped and compared against the locations of cold-end hardware / wear tags to help determine any possible relationships. The geographic location of all towers within each line is mapped as well. The Caribou-Palermo plot and map are shown in Figure 45 and Figure 46 respectively.

Many of the Caribou-Palermo wear damage tags are located within areas of elevated Aeolian time (highlighted in gray), and areas of elevated galloping time (highlighted in green), Figure 45. On the southern section of Caribou-Palermo, a high density of cold-end hardware wear tags are located in a region that has both elevated Aeolian time and towers that make use of link connections. Although some cold-end hardware / wear tags are co-located with high-wind towers (as highlighted in Figure 45), a large number of high-wind towers with no cold-end hardware / wear tags are observed. Further, wear tags are also present in areas of reduced wind speed, Aeolian, and galloping conditions. Thus, while wind is likely required to cause cold-end hardware wear, and the Caribou-Palermo line has the most aggressive wind conditions analyzed, no direct correlation between peak (50-year return) wind, Aeolian, or galloping conditions and high-priority wear tags can be made at this time.

Elevation, span weight (described in greater detail below), temperature, and precipitation also exhibit no obvious correlation to the presence of cold-end hardware wear or other wear-related tags, as shown in Figure 45. In addition to elevation, further analysis was also carried out on the terrain slope surrounding each tower, as peaks in elevation may correlate to elevated localized winds. Factors that make such environmental contributions difficult to characterize include effects of local terrain, as well as differences in maintenance, age, and design of structures and equipment.

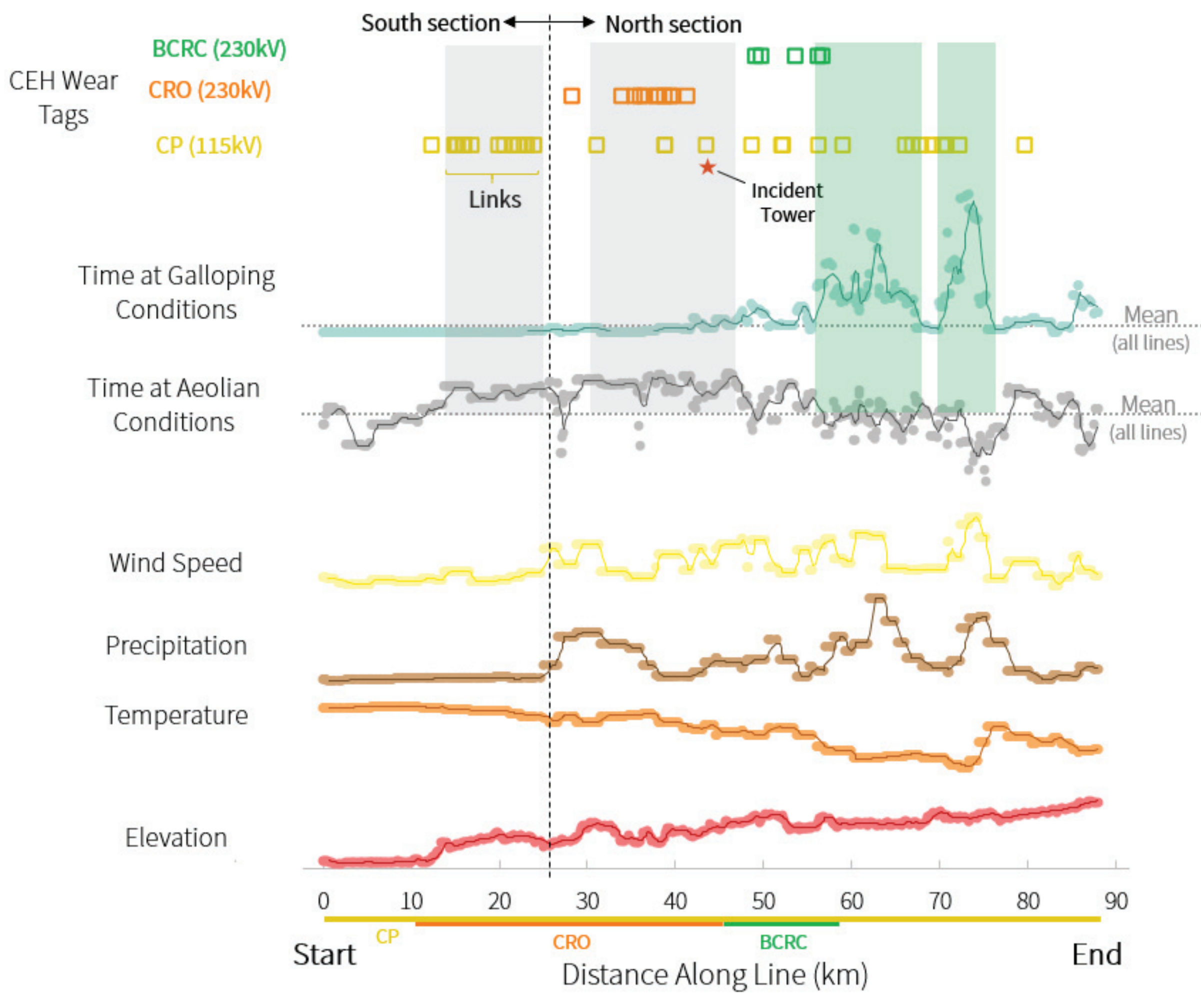


Figure 45. Factors vs. distance along line for the Caribou-Palermo line. All time-dependent data shown are averages of the full-year data from 2010. Areas of elevated Aeolian time (highlighted in gray), and areas of elevated galloping time (highlighted in green). CEH stands for cold-end hardware.

Comparison of Caribou-Palermo, CRO, and BCRC Wind Factors

Overlaying of the damage tags and wind conditions on each parallel line does not reveal obvious correlations between damage in one line vs. another. This suggests that wind conditions alone are not sufficient to describe the primary cause of damage in each tower. Other factors likely include differences in age of the structures, maintenance history, and tower/component design.

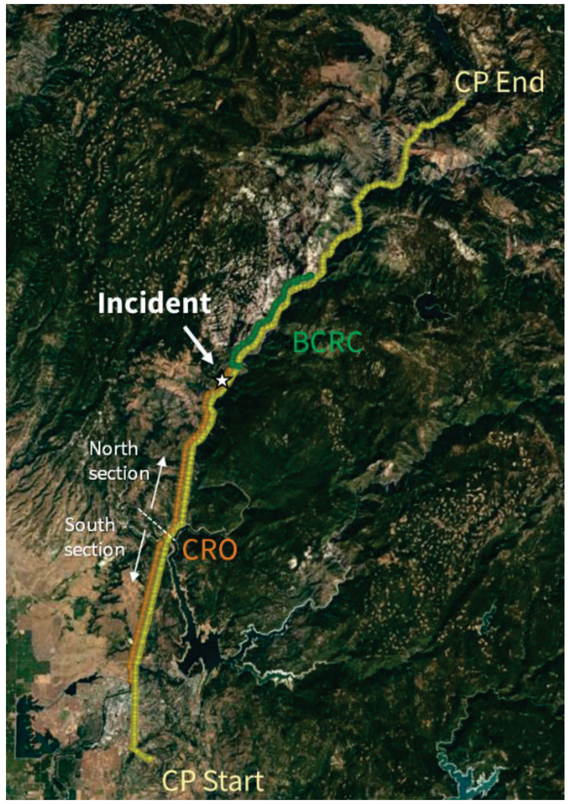


Figure 46. Map of all towers in the Caribou-Palermo line, and parallel lines Cresta–Rio Oso (CRO) and Bucks Creek–Rock Creek–Cresta (BCRC).

Span Distance

In addition to these wind and climate metrics, the tower-to-tower span distances and span weights were also calculated for each structure on Caribou-Palermo and selected comparison lines, Figure 47. The mean value of each category is calculated for each line, as well as the mean values of these categories for all towers with "A" damage tags, and all towers with cold-end hardware / wear tags.

The typical span distance between towers is roughly 200–260 m, with only a few lines (G12F, HM, HG) showing appreciably larger average distances. However, the variance in span distance is quite high, with some spans reaching distances greater than 500 m. No obvious correlation between span distance and damage tags is observed.

Span Weight

Span weight is calculated only for several adjacent lines where information on conductor type is available. Span weights were calculated from known conductor weights and GIS estimated span distances. These calculations are underestimates of span weights as they do not include conductor sag. However, comparison between BCRC, CRO, and Caribou-Palermo shows that Caribou-Palermo uses significantly lower weight conductors, leading to lower average span weights given the roughly similar average span distances, Figure 47. Tower-by-tower analysis of span weight is shown in Figure 48 for Caribou-Palermo. Lower span weights may increase susceptibility to wind-induced conductor motion.

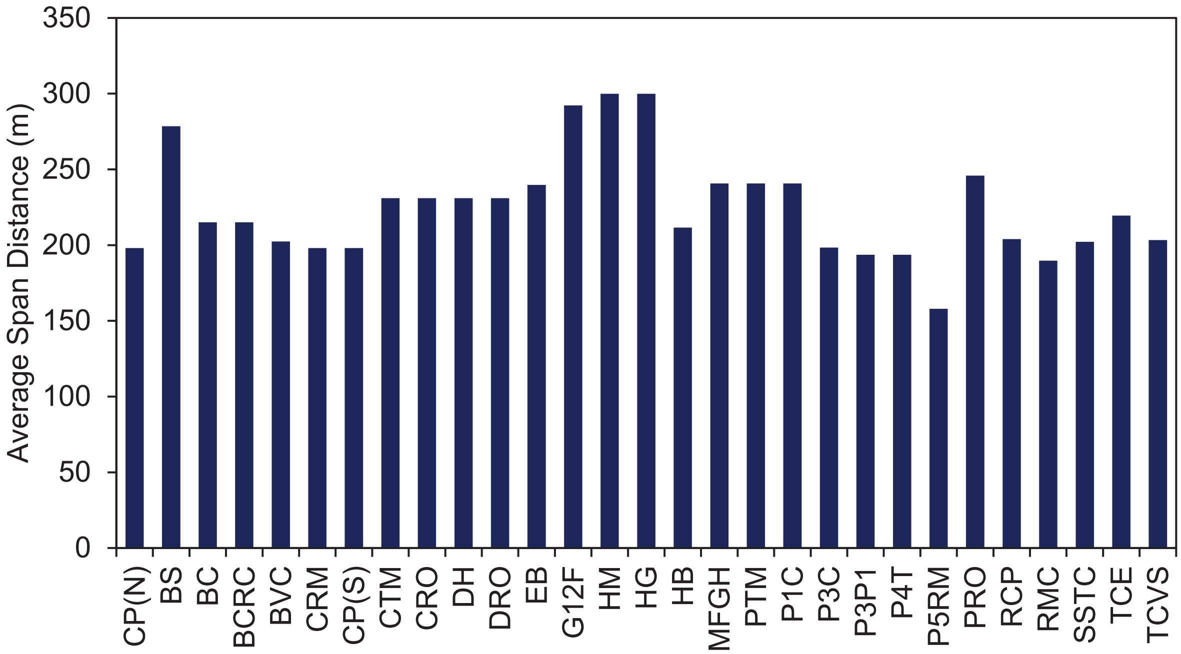


Figure 47. Average span distance measured across all towers in the given line.

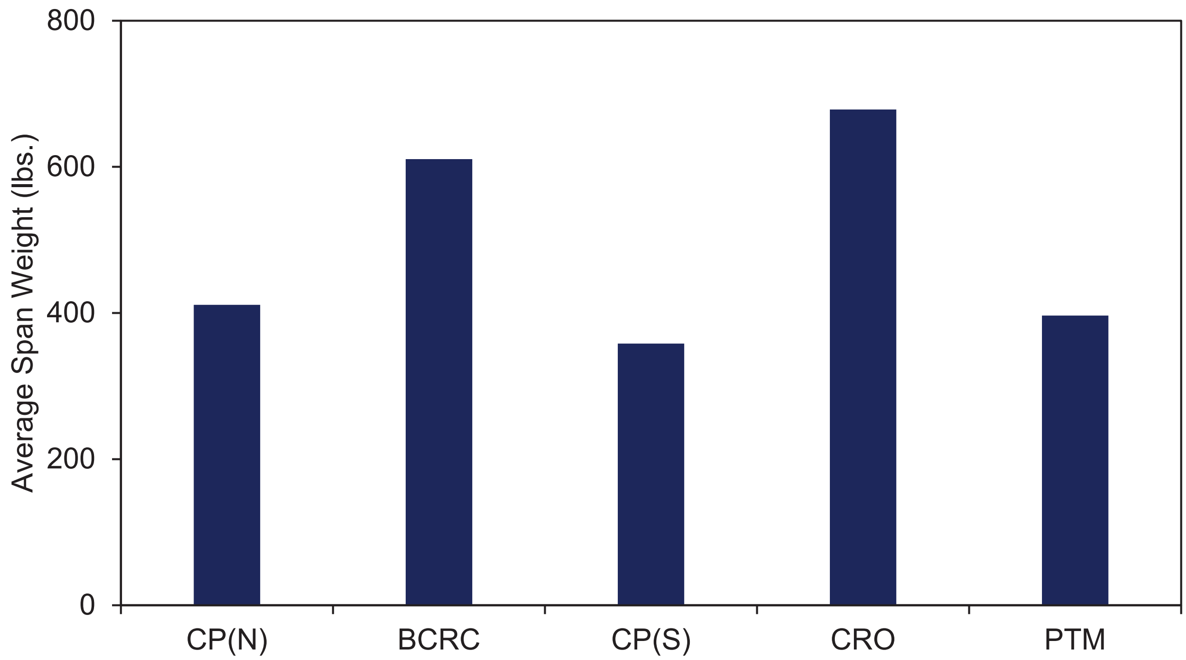


Figure 48. Average span weight measured across all towers in the given line.

Maintenance

The relatively high rate of wear-related high-priority tags observed on Caribou-Palermo after the Camp Fire suggests damage that has accumulated over years. To better understand the relevance of maintenance on Caribou-Palermo, the nature and frequency of historical repairs, including records of inspections, replacements, and corrective tags were analyzed. Selected comparison lines were also analyzed to create a relative comparison of historical maintenance.

Maintenance Districts

The PG&E electrical transmission system is divided into several maintenance districts. To assess how the comparison lines were distributed among these districts, and how tags might be clustered, post–Camp Fire high-priority tags were broken down by districts. A map of comparison lines broken down by maintenance district is shown in Figure 49. The Table Mountain district was found to have the highest number of tags, more than four times greater than the next highest district, Sacramento, Figure 50. However, upon normalizing for the number of steel lattice towers, the tag rate is very comparable to the Sacramento and Lakeville districts, Figure 51.

Figure 49. Map of comparison lines colored by maintenance district.

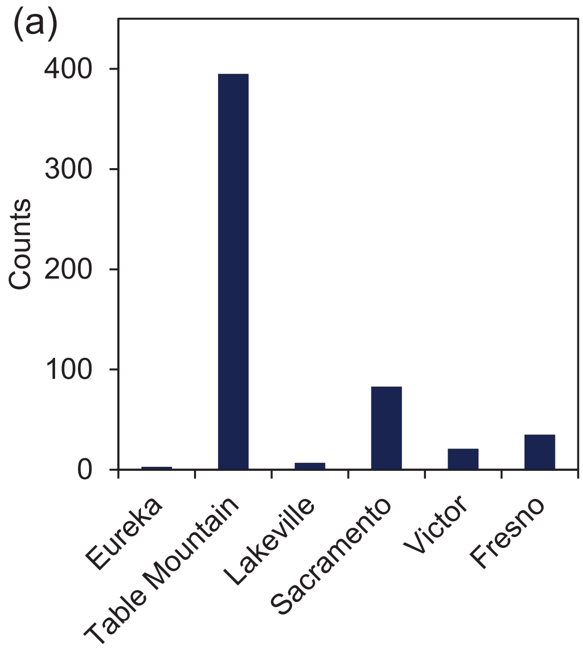


Figure 50. Post-Camp Fire high-priority (“A” and “B”) tag counts of maintenance districts for (a) steel lattice towers and (b) steel lattice towers above 1,000 ft.

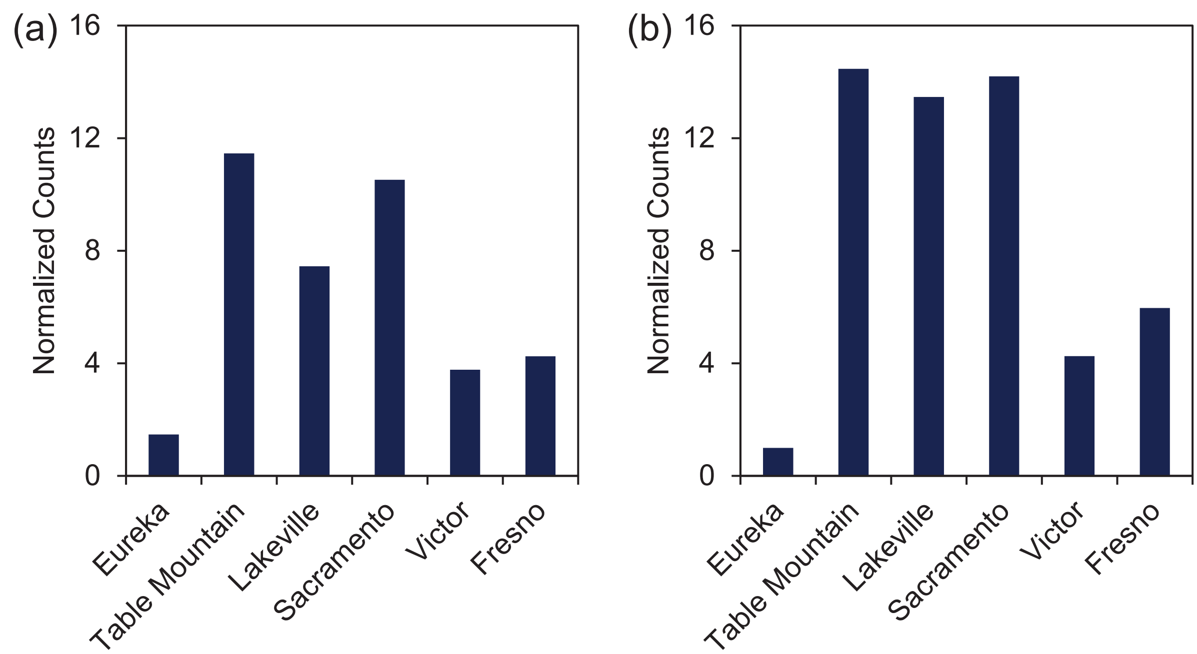


Figure 51. Post–Camp Fire high-priority (“A” and “B”) tag counts of maintenance districts for (a) steel lattice towers and (b) steel lattice towers above 1,000 feet normalized by the total number of steel lattice towers and steel lattice towers above 1,000 feet, respectively.

Pre–Camp Fire Climbing Inspections

Based on our meetings with PG&E SMEs, patrols and ground inspections typically did not include detailed climbing inspections of structures on lines less than 500 kV. However, in the months prior to the Camp Fire, PG&E did conduct climbing inspections on 79 Caribou-Palermo structures (one three-pole structure counted as one), as part of an aging asset inspection program. From September 19, 2018, to November 5, 2018, 45 structures on Caribou-Palermo South were climbing inspected, and 34 on Caribou-Palermo North, shown in Figure 52. A total of 141 inspector-noted issues were found. Exponent has binned the nonconformities noted during these inspections by component and inspector-noted priority, Figure 53. The letter priority rating utilized during these inspections has the same designations as post–Camp Fire inspections; however, the majority of issues found did not generate tags but rather were denoted "PC" or problem corrected. Because most inspector-noted nonconformities were corrected and did not result in a corrective action tag, we compare these inspections to post–Camp Fire Pronto inspection forms rather than post–Camp Fire tags.

The inspector-noted nonconformities during the post–Camp Fire climbing inspections were obtained from the Pronto forms associated with the same 79 structures. The inspector comments and nonconformity priority ratings from these forms were binned into components, as shown in Figure 54. These priority ratings were on a numerical scale, as follows, and were used as an estimate of damage level:

- 5 = Heavy Damage with Safety Concerns
- 4 = Heavy Damage
- 3 = Moderate Damage
- 2 = Light Damage
- 1 = No Visible Damage

Comparison between pre– and post–Camp fire inspections on the 79 Caribou-Palermo towers showed that a similar number of issues were noted, shown in Figure 55. However, the types and severity of issues differed. The majority of issues identified pre–Camp Fire were related to sealed foundations, missing signs, or loose or missing bolts. The issues identified post–Camp Fire included substantially more insulator and conductor-related damage, including those relating to both cold and hot-end hardware, Figure 54. The newly implemented enhanced inspection procedures, including the CIRT or DIRT review, appear to have led to substantial improvements in identifying progressive or wear-related damage near the tops of towers, particularly associated with cold- and hot-end hardware.

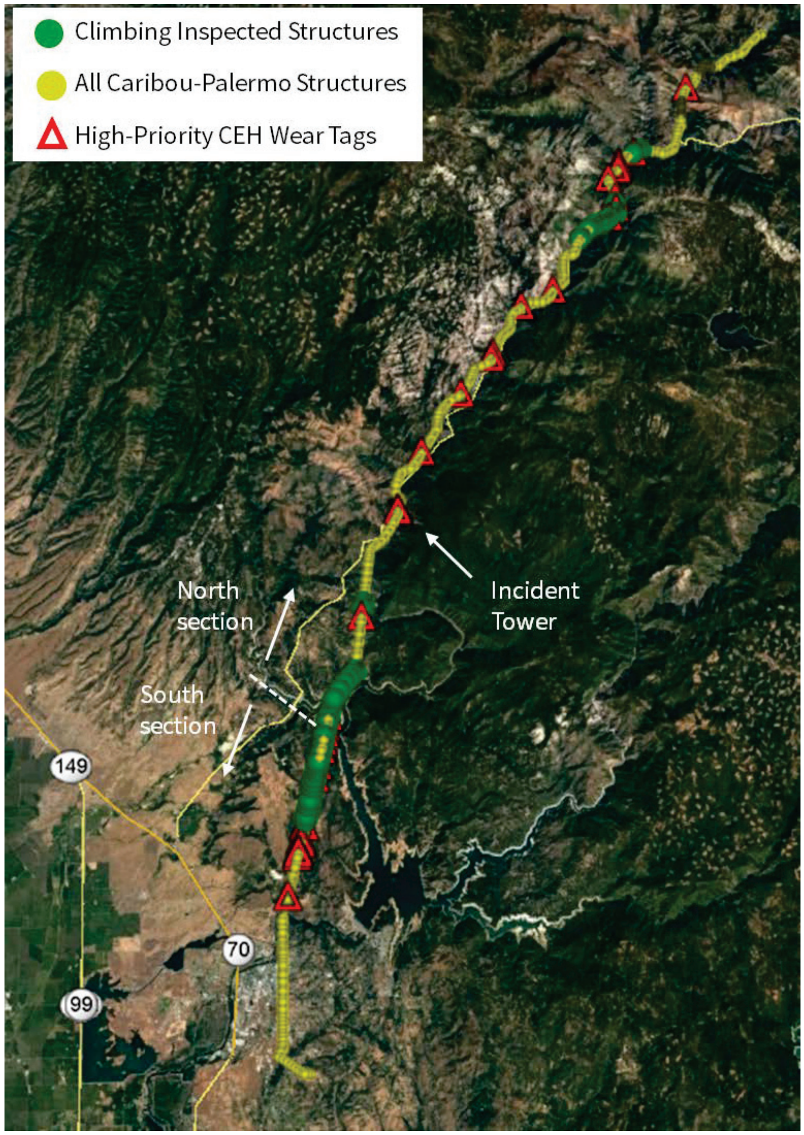


Figure 52. Map of structures that underwent a climbing inspection from September 19, 2018, to November 5, 2018.

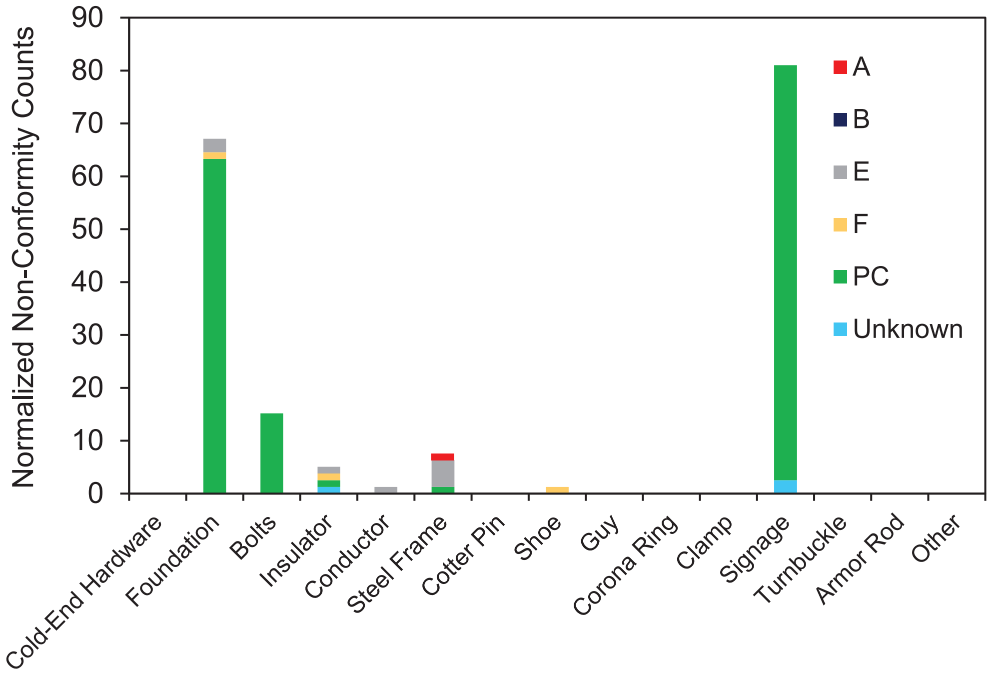


Figure 53. Inspector-noted nonconformities from pre–Camp Fire climbing inspections on 79 towers binned by component. Priorities were assigned by the inspector and were not reviewed by CIRT. Designations have the same repair timescale as post–Camp Fire tags. PC stands for problem corrected and was indicated when the issue was repaired by the inspector.

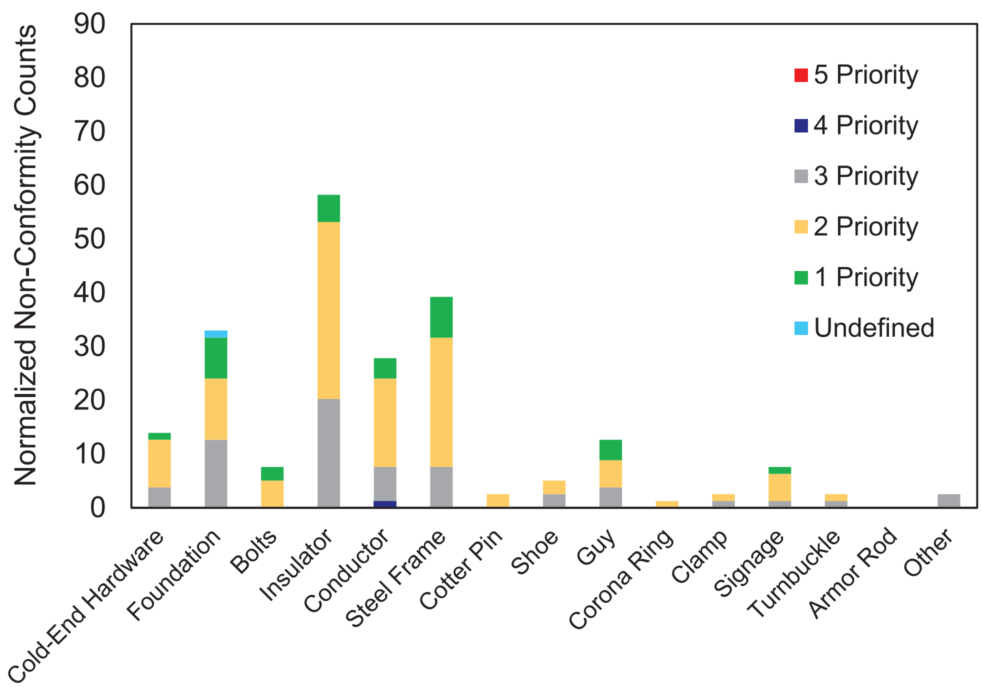


Figure 54. Binned post–Camp Fire inspector-noted nonconformities from the same 79 structures as Figure 53, obtained from Pronto forms.

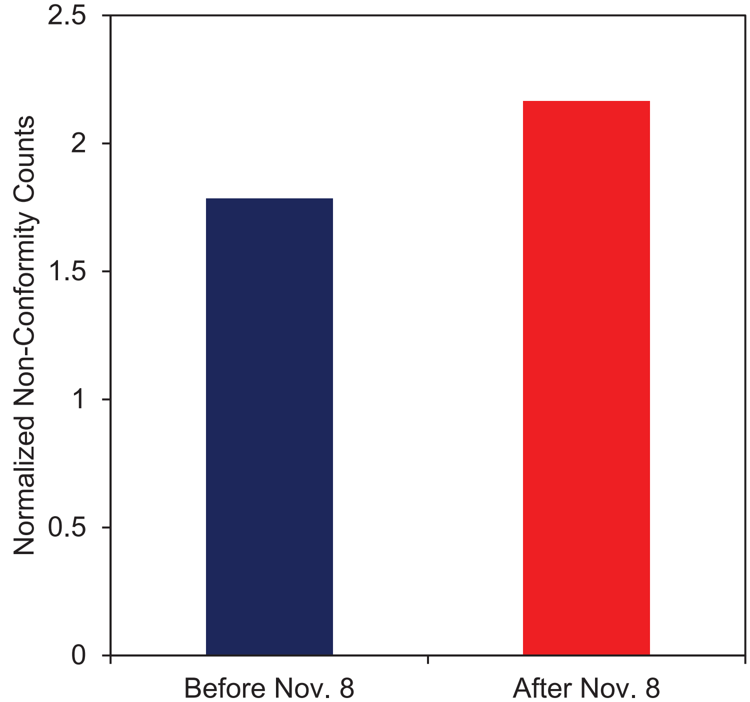


Figure 55. Comparison of the number of inspector-noted nonconformities from pre– and post–Camp Fire climbing inspections.

Inspection Frequency

Caribou-Palermo and comparison lines were subject to periodic ground inspections. In addition, ground or air patrols were performed during years without ground inspections. The PG&E Electric Transmission Preventive Maintenance Manual (ETPM) defines a patrol as walking, driving, or flying (helicopter only) visual observation of structures to identify abnormalities, i.e., obvious structural problems or hazards or circumstances that will negatively impact safety. An inspection is defined as a detailed visual observation of individual components that will negatively impact safety, reliability, or asset life. Figure 56 shows the average time interval between ground inspections for Caribou-Palermo and selected comparison lines between January 2001 and October 2018. The average interval between ground inspections across these lines was 2.8 years. Caribou-Palermo received ground inspections every 2.8 years on average, similar to the inspection frequency for comparison lines.

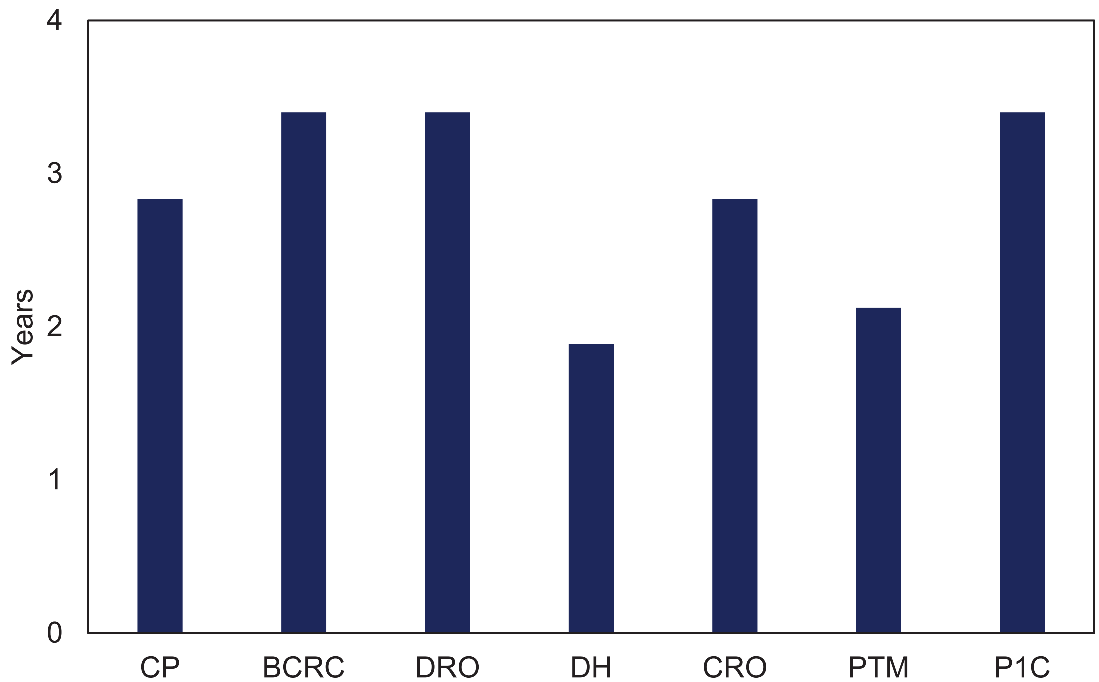


Figure 56. Average time interval between ground inspections for select comparison lines over the period from January 2001 to October 2018.

Historical Tag Counts

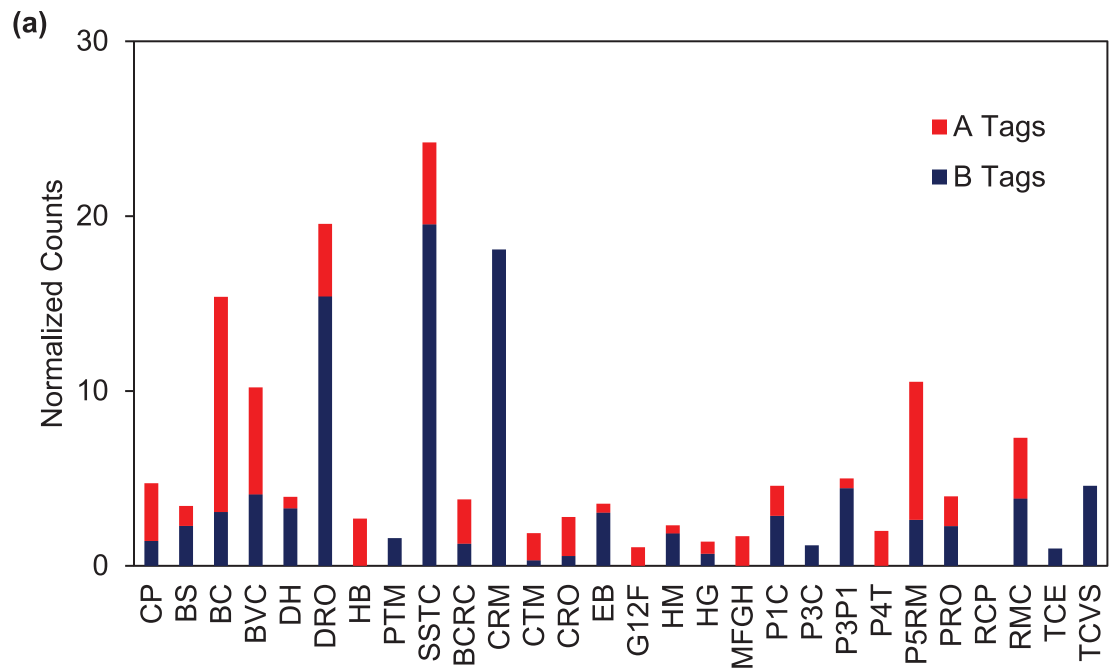
The number of high-priority tags per line over the period from January 2001 through October 2018 was tallied for the full set of 28 comparison lines. From 2001 to 2007, tags were prioritized on a scale of 1 to 6, according to the scheduled time to completion for repairs:

- "1" – Force out / work now
- "2" – 90 days
- "3" – 1–6 months
- "4" – 6–12 months
- "5" – 24 months
- "6" – more than 24 months

To compare pre-2008 tags with more recent tags, the 1–6 priority scale was converted to the present A–F priority scale:

- 1 = A – Perform corrective action immediately.
- 2 = B – Perform corrective action within three months.
- 3 or 4 = E – Perform corrective action within one year.
- 5 or 6 = F – Perform corrective action in more than one year.

For the following analysis, only high-priority (“1,” “2” / “A,” and “B”) tags were considered. To compare tag counts across lines, counts were normalized using the same method as described in the “Line Comparison and Normalization Methodology” section. The high-priority tag count for Caribou-Palermo was similar to comparison lines prior to November 2018. In Figure 57(a), the normalized high-priority tag counts from January 2001 through October 2018 are tallied for steel lattice towers on Caribou-Palermo and comparison lines. The average normalized steel lattice tower tag count across all comparison lines was 6.1 over this time period, compared to a normalized count of 4.7 on Caribou-Palermo. Figure 57(b) shows the normalized tag counts for high-priority tags on the subset of steel lattice towers over 1,000 feet in elevation. For steel lattice towers over 1,000 feet, the average normalized count was 6.7, compared to a normalized count of 5.4 on Caribou-Palermo North.



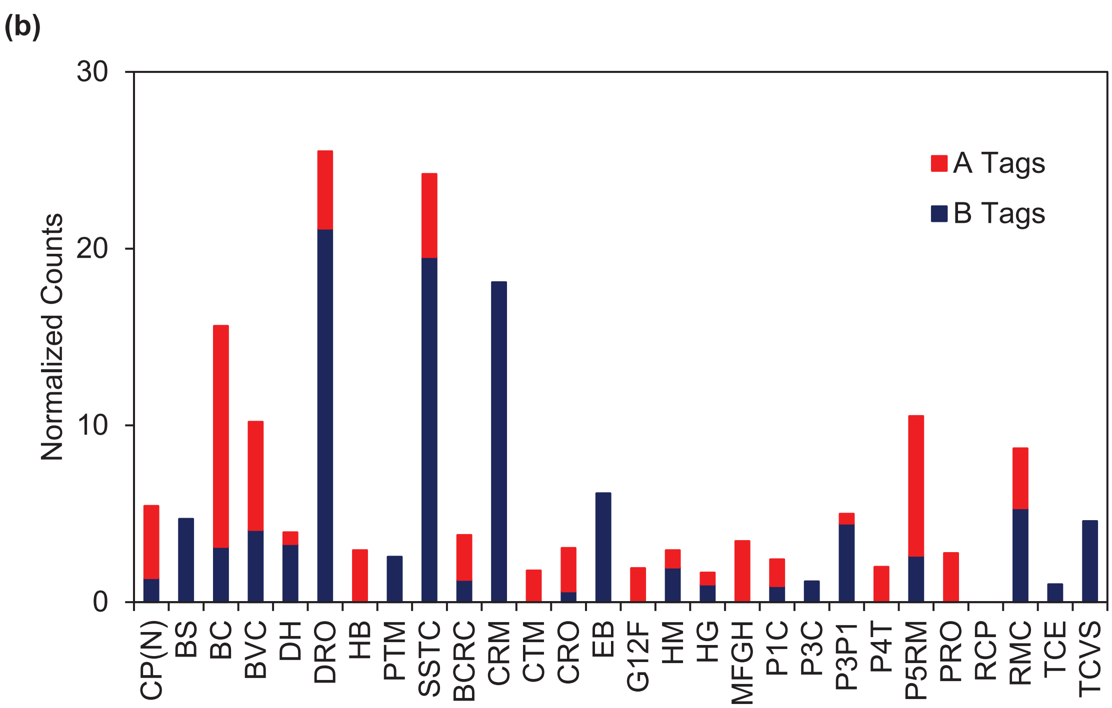


Figure 57. Cumulative normalized “A” and “B” tag counts associated with steel lattice towers on entire Caribou-Palermo line and comparison lines (a) and steel lattice towers over 1,000 feet (b) for the period from January 2001 to October 2018.

Analysis of Components and Damage Modes in Caribou-Palermo Historical Tags

Historical high-priority (converted to "A" and "B") Caribou Palermo tags were binned by component type and damage mode using the same approach as described in the "Post-Camp Fire Caribou-Palermo Tag Analysis" section. In Figure 58, a breakdown of the component types and damage modes shows that steel frame and conductor related issues accounted for the highest number of historical tags. No high-priority tags associated with cold-end hardware wear were found. A review of historical tags for comparison lines also found no high-priority cold-end hardware / wear tags during the period from January 2001 through October 2018.

Examples of forms used during patrols and inspections were reviewed for indications of whether hanger plates and associated cold-end hardware were subject to regular inspection. Detailed climbing inspection forms used before and after the institution of WSIP did contain fields specifically designated for assessing cold-end hardware wear. However, prior to WSIP, detailed climbing inspections were reportedly not routinely performed for Caribou-Palermo and the comparison lines. Example forms for ground inspections and patrols did not include fields specified for assessing cold-end hardware wear.

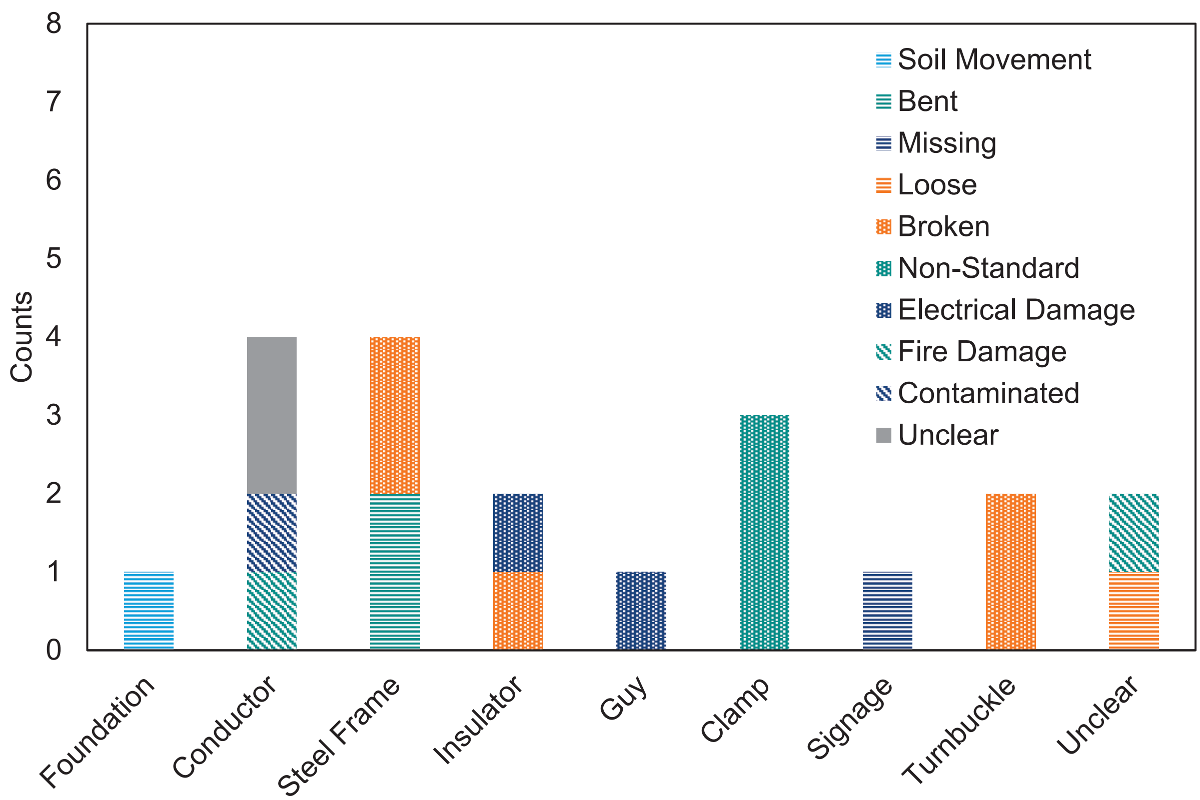


Figure 58. High-priority tag counts broken down by component type and damage mode for Caribou-Palermo over the period from January 2001 through October 2018.

Historical Outage Performance

The historical rate of power outages on Caribou-Palermo was examined in comparison with other electric transmission lines (ETLs) in WSIP. The outage data was provided by a PG&E SME for an 11-year period (2007–2018), and was filtered to include only unplanned and equipment-related outages (including outages caused by equipment failure, weather, and non-animal contamination). The ETLs were ranked by the number of equipment-related outages, normalized by total days of outage history (i.e., 365 days in a year times 11 years) and circuit length (in miles), as shown in Figure 59. The circuit length was obtained from PG&E's ET-GIS database. Based on the data, a total of 159 of the 551 ETLs in WSIP had zero recorded outages during this period. In addition, 7 of the 551 ETLs were foreign lines with no outage data available (null values). Caribou-Palermo experienced 38 equipment-related outages, more per-mile per-day than approximately 80 percent of the other WSIP lines. Among the 28 comparison lines, only Butte Valley–Caribou and Paradise–Table Mountain experienced more outages per-mile per-day. Other lines in the North Fork Feather River Canyon, labeled on the plot in Figure 59, exhibited a wide range of outage performance.